Journal of Clinical and Nursing Research, 2024, Volume 8, Issue 9
http://ojs.bbwpublisher.com/index.php/JCNR
Online ISSN: 2208-3693
Print ISSN: 2208-3685

Application of Personalized 3D-Printed Rehabilitation Orthotics in Postoperative Recovery of Jaw Fractures

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Abstract: *Objective:* To analyze the effectiveness of personalized 3D-printed rehabilitation orthotics in the postoperative recovery of jaw fractures. *Methods:* Relevant data were collected from 42 patients with jaw fractures treated at our hospital between October 2017 and May 2020. Patients were randomly divided into a traditional group (n = 17) and a modified group (n = 25). The traditional group received standard rehabilitation methods, while the modified group used personalized 3D-printed rehabilitation orthotics combined with improved rehabilitation methods. The temporomandibular disability index (TDI), quality of life scores, postoperative recovery excellence rate, and mouth opening were compared between the two groups at different follow-up times (before rehabilitation, and at 1 week, 3 months, and 6 months post-surgery). *Results:* At 1 week, 3 months, and 6 months post-surgery, the TDI in both the traditional and modified groups was significantly lower than before rehabilitation, with statistically significant differences ($P < 0.05$). At 3 and 6 months post-surgery, the TDI in the modified group was lower than in the traditional group, with statistically significant differences ($P < 0.05$). At 3 and 6 months post-surgery, pain, appearance, activity, recreation, work, chewing, swallowing, speech, shoulder function, and total quality of life scores in both groups were higher than before rehabilitation, with the modified group showing significantly higher scores in pain, appearance, chewing, swallowing, and total quality of life ($P < 0.05$). Compared to before rehabilitation, mouth opening significantly improved in both groups at 3 and 6 months post-surgery, with the modified group showing significantly greater improvement ($P < 0.05$). *Conclusion:* Personalized 3D-printed rehabilitation orthotics are highly effective in the postoperative recovery of jaw fractures. They can improve patients' quality of life after surgery, enhance the excellent rate of postoperative recovery, and increase mouth opening.

Keywords: Personalized 3D printing; Rehabilitation orthotics; Jaw fracture

Online publication: September 27, 2024

1. Introduction

In recent years, with the continuous improvement of medical rehabilitation standards, the postoperative rehabilitation of jaw fractures has garnered increasing attention [1,2]. Studies have found that timely and effective functional rehabilitation training after surgery significantly promotes mandibular function recovery in patients with jaw fractures, enhances their quality of life, and contributes to early recovery [3]. Currently, postoperative rehabilitation methods for jaw fractures mainly include mouth-opening exercises and lateral mandibular movements, but these methods often fail to achieve satisfactory rehabilitation outcomes [4]. Most domestic and international research has focused on comparing the effectiveness of conservative and surgical treatments for jaw fractures, with limited studies on postoperative rehabilitation training [5].

3D printing technology, which emerged in the 1980s, is a novel digital manufacturing technology that creates complex forms by accurately layering materials based on computer-controlled designs or computed tomography data [6]. Currently, 3D printing technology is mainly applied in areas such as stereolithography, three-dimensional inkjet printing, and selective laser sintering. It holds unique advantages in the medical field, such as creating physical molds for bone defects, assisting doctors in producing personalized implants to improve surgical efficiency, and preparing biological scaffolds [7].

This study compares the effects of personalized 3D-printed rehabilitation orthotics combined with modified rehabilitation methods versus traditional rehabilitation methods on postoperative rehabilitation training for jaw fractures, aiming to explore the application effectiveness of personalized 3D-printed rehabilitation orthotics and provide new insights into postoperative rehabilitation training for jaw fractures.

2. Materials and methods

2.1. General information

Data were collected from 42 patients who underwent jaw fracture surgery at Xi'an Jiaotong University Stomatological Hospital between October 2017 and May 2020. Cases were screened according to inclusion and exclusion criteria and were randomly divided into the traditional group (n = 17) and the modified group (n = 25). In the traditional group, there were 9 males and 8 females with an average age of 39.12 ± 13.07 years. In the modified group, there were 14 males and 11 females with an average age of 37.88 ± 10.70 years. The comparison of general information showed no statistical significance ($P > 0.05$). This study was reviewed by the ethics committee and meets the requirements of medical ethics (Ethics Approval No.: 2021060[2021] NO.223), and all patients signed informed consent forms.

Inclusion criteria: (1) Age ≥ 18 years; (2) Diagnosed with jaw fracture by CBCT or other methods; (3) Met surgical indications and underwent open reduction and internal fixation surgery; (4) Complete medical records with all necessary examinations; (5) Postoperative rehabilitation treatment conducted; (6) Good postoperative wound healing; (7) Follow-up period of no less than 6 months.

Exclusion criteria: (1) History of temporomandibular joint disorders; (2) Patients with mental illness or cognitive impairment; (3) Patients undergoing orthodontic treatment; (4) Patients with blood or immune system diseases; (5) Other malignant diseases.

2.2. Methods

The traditional group used traditional rehabilitation methods. Patients underwent routine mouth-opening

exercises, mandibular protrusion-retraction movements, and lateral mandibular movements during the 1–4 weeks postoperatively. In the first stage, three types of exercises were alternated. In the second stage, one month after treatment, passive mouth-opening exercises were added based on the patient's mouth-opening degree, using traditional rehabilitation orthotics to assist in the exercises.

The modified group used personalized 3D-printed rehabilitation orthotics combined with modified rehabilitation methods based on those of the traditional group. Specifically, patients' CT scan data were imported into the 3D Slicer software to obtain a 3D model of the teeth. Based on the patient's mouth-opening degree, the 3DMax software was used to design a rehabilitation orthotic tailored to the patient's own teeth. The model data was exported as a ".stl" file and imported into the MakerBot Print slicing software. The "Draft" printing mode was selected, with a fill rate of 20%. After slicing, the file was exported as ".makerbot" and connected to a 3D printer to produce the personalized rehabilitation orthotic. The modified rehabilitation method also included additional training such as mandibular-neck muscle relaxation, temporomandibular joint muscle relaxation, temporomandibular joint stability, temporomandibular joint mobility, and temporomandibular joint passive stretching. In the first stage of rehabilitation training, PEMF therapy and shortwave therapy were also added.

2.3. Observation indicators

2.3.1. Temporomandibular disability index

The temporomandibular disability index (TDI) of both groups was recorded before rehabilitation treatment and at 1 week, 3 months, and 6 months postoperatively [8]. This index is used to assess the impact of the disease on patients' daily lives, covering 10 dimensions including communication, daily living abilities, and sleep. Each item is scored on a 5-point Likert scale, with higher scores indicating greater impact on the patient. The total score is 40 points.

2.3.2. Quality of life

The UW-QOL [9] was used to analyze the quality-of-life scores of both groups before rehabilitation treatment and at 1 week, 3 months, and 6 months postoperatively. The UW-QOL covers 9 dimensions, each with a maximum score of 100 points, for a total of 900 points. The UW-QOL score is positively correlated with patients' quality of life.

2.3.3. Rehabilitation effectiveness rate

At 6 months postoperatively, the rehabilitation effectiveness rate of both groups was assessed. The evaluation criteria were [10]:

(1) Excellent: Good recovery of occlusal relationships, fracture sites, and mouth-opening degree, with a mouth-opening degree > 30 mm and no pain.

(2) Good: Fracture displacement < 10mm, satisfactory recovery of occlusal relationships and fracture sites, but not optimal, with remaining gaps between upper and lower molars, mouth-opening degree > 20 mm, and reduced pain.

(3) Poor: Occlusal relationships, fracture displacement, mouth-opening degree, and pain did not meet the above standards.

The effectiveness rate = (Excellent + Good) / Total number of cases × 100%.

2.3.4. Mouth-opening degree

The mouth-opening degree of both groups was recorded before rehabilitation treatment and at 1 week, 3 months, and 6 months postoperatively. The mouth-opening degree refers to the maximum vertical distance between the upper and lower incisors when the mouth is opened.

2.4. Statistical analysis

Data processing in this study was performed using SPSS 20.0 software. Categorical data were represented as [*n* (%)], and chi-squared (χ^2) tests were used for analysis. For continuous data that conformed to a normal distribution, independent sample *t*-tests were used for comparisons between the two groups, while repeated measures ANOVA was used for intra-group comparisons at different time points. The significance level was set at $P = 0.05$.

3. Results

3.1. Comparison of TDI at different treatment times between the two groups

The comparison of TDI at different treatment times between the traditional group and the modified group showed statistically significant differences ($P < 0.05$). Specifically, at 1 week, 3 months, and 6 months postoperatively, the TDI in both the traditional and modified groups was lower than before rehabilitation treatment, with statistically significant differences ($P < 0.05$). There was no statistically significant difference in TDI between the two groups before rehabilitation treatment and at 1 week postoperatively ($P > 0.05$). However, at 3 months and 6 months postoperatively, the TDI in the modified group was lower than that in the traditional group, with statistically significant differences ($P < 0.05$). See **Table 1**.

Table 1. Comparison of TDI at different treatment times between the two groups (mean ± SD, points)

Groups	Before rehabilitation	1 week after surgery	3 months after surgery	6 months after surgery	*F*	*P*
Traditional group ($n = 17$)	32.10 ± 5.31	26.54 ± 5.16*	24.60 ± 4.28*	22.66 ± 3.34*	32.436	< 0.001
Modified group ($n = 25$)	32.50 ± 4.76	24.89 ± 4.41*	21.42 ± 3.90*	19.07 ± 2.79*	57.095	< 0.001
t	0.279	1.215	2.531	3.768		
P	0.802	0.230	0.020	< 0.001		

Note: *Compared with before rehabilitation treatment, $P < 0.05$.

3.2. Comparison of quality-of-life scores at different treatment times between the two groups

At 3 months and 6 months postoperatively, the UW-QOL scores in various dimensions and the total quality of life scores in both the traditional and modified groups were significantly higher than before rehabilitation treatment ($P < 0.05$). At 3 months and 6 months postoperatively, the pain, appearance, chewing, swallowing, and total quality of life scores in the modified group were significantly higher than those in the traditional group ($P < 0.05$). See **Table 2**.

Table 2. Comparison of quality-of-life scores at different treatment times between the two groups (mean ± SD, points)

Duration of treatment		Traditional group (n = 17)	Modified group (n = 25)	t	P
Soreness	Before rehabilitation	34.10 ± 4.58	33.54 ± 3.36	0.433	0.667
	1 week after surgery	34.54 ± 4.05	34.90 ± 4.36	0.271	0.788
	3 months after surgery	60.26 ± 4.69*	73.34 ± 5.36*	8.226	< 0.001
	6 months after surgery	75.50 ± 5.11*	85.52 ± 6.11*	5.620	< 0.001
Appearance	Before rehabilitation	41.50 ± 4.59	41.02 ± 5.33	0.292	0.772
	1 week after surgery	43.40 ± 3.49	44.10 ± 4.53	0.563	0.577
	3 months after surgery	48.80 ± 5.11*	56.64 ± 5.06*	4.857	< 0.001
	6 months after surgery	60.30 ± 4.82*	73.34 ± 7.31*	6.635	< 0.001
Function	Before rehabilitation	35.56 ± 5.03	34.98 ± 4.17	0.445	0.659
	1 week after surgery	36.30 ± 4.21	37.28 ± 3.36	0.764	0.449
	3 months after surgery	58.86 ± 5.33*	59.90 ± 6.42*	0.579	0.566
	6 months after surgery	92.50 ± 5.36*	93.16 ± 5.37*	0.389	0.699
Recreation	Before rehabilitation	32.30 ± 3.41	33.16 ± 3.28	0.813	0.421
	1 week after surgery	35.00 ± 5.11	35.30 ± 4.51	0.171	0.865
	3 months after surgery	70.34 ± 6.12*	71.16 ± 4.81*	0.477	0.636
	6 months after surgery	94.36 ± 6.12*	95.24 ± 7.73*	0.431	0.669
Work	Before rehabilitation	37.40 ± 4.85	36.80 ± 5.51	0.353	0.726
	1 week after surgery	38.86 ± 4.59	39.00 ± 4.66	0.123	0.903
	3 months after surgery	74.88 ± 6.37*	75.50 ± 8.75*	0.285	0.777
	6 months after surgery	93.34 ± 7.19*	94.42 ± 8.04*	0.435	0.666
Chewing	Before rehabilitation	31.26 ± 5.25	31.60 ± 4.33	0.217	0.829
	1 week after surgery	32.10 ± 6.03	33.04 ± 5.31	0.518	0.607
	3 months after surgery	55.60 ± 5.91*	64.46 ± 7.44*	4.170	< 0.001
	6 months after surgery	75.50 ± 8.82*	83.10 ± 8.76*	2.738	0.009
Swallowing	Before rehabilitation	33.42 ± 3.37	33.04 ± 5.18	0.268	0.790
	1 week after surgery	35.00 ± 4.06	35.16 ± 4.12	0.131	0.896
	3 months after surgery	60.25 ± 7.14*	68.85 ± 6.23*	4.068	< 0.001
	6 months after surgery	81.80 ± 6.82*	89.30 ± 8.54*	3.077	0.004
Speech	Before rehabilitation	32.30 ± 5.04	32.15 ± 4.29	0.081	0.936
	1 week after surgery	34.40 ± 4.95	35.05 ± 5.19	0.380	0.706
	3 months after surgery	73.15 ± 6.87*	72.20 ± 6.18*	0.446	0.658
	6 months after surgery	99.15 ± 5.02*	99.30 ± 4.57*	0.112	0.911
Shoulder function	Before rehabilitation	78.90 ± 4.39	79.10 ± 3.34	0.178	0.860
	1 week after surgery	80.05 ± 5.88	80.55 ± 5.51	0.289	0.774
	3 months after surgery	92.15 ± 10.22*	93.00 ± 6.59*	0.320	0.751
	6 months after surgery	98.20 ± 13.35*	98.50 ± 8.34*	0.094	0.926
Totals	Before rehabilitation	355.60 ± 25.48	356.00 ± 22.31	0.057	0.955
	1 week after surgery	367.75 ± 33.48	375.55 ± 32.15	0.752	0.457
	3 months after surgery	562.35 ± 51.26*	634.45 ± 45.86*	4.687	< 0.001
	6 months after surgery	768.30 ± 73.34*	810.95 ± 50.33*	2.146	0.038

Note: *Compared with before rehabilitation treatment, $P < 0.05$.

3.3. Comparison of rehabilitation effectiveness rate between the two groups

Table 3 shows that the rehabilitation effectiveness rate in the modified group was significantly higher than that in the traditional group (92.00% vs. 64.71%; $P < 0.05$).

Table 3. Comparison of rehabilitation effectiveness rate between the two groups [*n* (%)]

Groups	Excellent	Good	Poor	Effectiveness rate
Traditional group ($n = 17$)	8 (47.06)	3 (17.65)	6 (35.29)	11 (64.71)
Modified group ($n = 25$)	16 (64.00)	7 (28.00)	2 (8.00)	23 (92.00)
P				0.045

3.4. Comparison of mouth-opening degree at different treatment times between the two groups

The comparison of mouth-opening degree at different treatment times between the traditional group and the modified group showed statistically significant differences ($P < 0.05$). At 1 week postoperatively, there was no statistically significant difference in mouth-opening degree between the traditional group and the modified group compared with before rehabilitation treatment ($P > 0.05$). However, at 3 months and 6 months postoperatively, the mouth-opening degree in both the traditional and modified groups was significantly higher than before rehabilitation treatment and at 1 week postoperatively ($P < 0.05$). At 6 months postoperatively, the mouth-opening degree in both the traditional and modified groups was significantly higher than at 3 months postoperatively ($P < 0.05$).

There was no statistically significant difference in mouth-opening degree between the two groups before rehabilitation treatment and at 1 week postoperatively ($P > 0.05$). However, at 3 months and 6 months postoperatively, the mouth-opening degree in the modified group was significantly higher than that in the traditional group ($P < 0.05$). See **Table 4**.

Table 4. Comparison of mouth-opening degree at different treatment times between the two groups (mean ± SD, mm)

Groups	Before rehabilitation	1 week after surgery	3 months after surgery	6 months after surgery	*F*	*P*
Traditional group ($n = 17$)	14.33 ± 3.89	16.99 ± 5.05	29.13 ± 4.57*$^{\#}$	40.29 ± 4.67*$^{\#\dagger}$	98.742	< 0.001
Modified group ($n = 25$)	15.04 ± 5.13	17.30 ± 4.36	36.74 ± 4.86*$^{\#}$	44.20 ± 3.39*$^{\#\dagger}$	250.288	< 0.001
t	0.484	0.216	4.825	3.142		
P	0.631	0.830	< 0.001	0.003		

Note: *Compared with before rehabilitation treatment, $P < 0.05$; $^{\#}$Compared with 1 week postoperatively, $P < 0.05$; †Compared with 3 months postoperatively, $P < 0.05$.

4. Discussion

The personalized 3D-printed rehabilitation orthotic is designed based on the patient's dental conditions. Using CT images, the anatomical structure of the teeth is obtained, and a digital model of the teeth is constructed. Modeling software designs and 3D printing technology reconstruct a rehabilitation orthotic that is more

ergonomically suited to the patient [11]. This ensures that the force distribution is uniform during occlusion, avoids loose teeth, and makes mouth-opening support and training more convenient. Additionally, the 3D printing material, polylactic acid (PLA), is very safe, and the rehabilitation orthotic is an auxiliary tool. The entire process is non-invasive and highly safe [12,13].

The temporomandibular disability index is an effective indicator for assessing temporomandibular function, primarily used to evaluate the impact of mandibular dysfunction on the patient's daily life. This study found that compared with before rehabilitation treatment, the TDI of patients in both groups significantly improved at 3 months and 6 months postoperatively. This may be due to the surgery providing strong support for the restoration of the anatomical structure of the dentofacial system. The modified group was significantly better than the control group, possibly because traditional rehabilitation orthotics are fixed and do not fit tightly with the teeth, leading to discomfort during training and insufficient systematic training focusing only on mandibular protrusion and retraction movements. The modified group, using a combination of improved rehabilitation methods and personalized 3D-printed orthotics, provided a better patient experience, higher cooperation during training, and facilitated sliding exercises of the temporomandibular joint, thereby reducing the impact of mandibular dysfunction on daily life [14].

This study also found that at 3 months and 6 months postoperatively, the scores for pain, appearance, activity, entertainment, work, chewing, swallowing, speech, shoulder function, and overall quality of life were all higher than before rehabilitation treatment in both the traditional and modified groups. The modified group showed superior scores in pain, appearance, chewing, swallowing, and overall quality of life compared to the traditional group. This might be because the personalized 3D-printed rehabilitation orthotic effectively exercised the patient's mandibular function during the improved rehabilitation process, leading to improved mandibular function. During training, active and resistance training, PEMF therapy, and ultrashort wave therapy inhibited scar formation and tissue hardening in the temporomandibular joint, accelerating the recovery of the masticatory muscle group and thereby improving the patient's quality of life.

The rehabilitation effectiveness rate and the degree of mouth opening at 3 and 6 months postoperatively were better in the modified group than in the traditional group. This may be due to the lack of systematic rehabilitation training in the traditional group. Under the modified rehabilitation method, early postoperative systematic training strengthened the duration of patient training, accelerated the recovery of various functional activities, and combined with the personalized 3D-printed rehabilitation orthotic, further enhanced the interaction between muscles and bones, promoting the recovery of mandibular function, reducing joint asymmetry, and further improving rehabilitation outcomes and mouth-opening degrees [15,16].

In summary, compared to traditional rehabilitation methods, the combination of improved rehabilitation methods and personalized 3D-printed rehabilitation orthotics has a significant effect on post-fracture rehabilitation of the jaw, improving postoperative quality of life, achieving better rehabilitation outcomes, and enhancing mouth-opening degrees. However, as 3D printing equipment is not yet widely available, further multicenter, randomized studies with more cases are needed in the future to corroborate these findings.

Funding

Open Subject of Clinical Research Center of Shaanxi Province for Dental and Maxillofacial Diseases, College of Stomatology, Xi'an Jiaotong University (Project No. 2011YHJB08)

Disclosure statement

The authors declare no conflict of interest.

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