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The treatment experience of artificial muscle type dynamic splint for patients with chronic nature of wrist joint contractures

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Abstract

Dart-throwing motion has attracted attention as a functional and novel movement. To date, wrist joint splints regarding traction function and dart-throwing motion with a single splint have been hardly investigated. Therefore, a new artificial muscle-type dynamic traction splint incorporating this novel motion pattern was devised, aiming to investigate the therapeutic use of the dynamic traction splint by artificial muscle in patients with wrist joint contractures. Four hands of three patients diagnosed with wrist joint contractures were assessed. The average splint usage period was 5 weeks. The wrist joint range of motion and grip strength were evaluated initially and after 5 weeks. The wrist joint range of motion was evaluated over a 6-week period. The splints were required to be worn four times. The traction force was initiated at 500 kPa and was appropriately altered based on patient symptoms. The mean (±standard deviation) palmar flexion angle was 21.3° (±5.4) initially and 43.8° (±9.7) at 5 weeks; the improvement in the angle was 22.5°. The mean dorsal flexion angle was 16.3° (±4.4) initially and 45.0° (±6.9) at 5 weeks; the improvement in the angle was 28.7°. The grip strength improved from 15.7% of the healthy side at the start to 72.5% after 5 weeks. These results indicated that therapeutic outcomes with the dynamic traction splint by artificial muscle were almost the same as those with rehabilitation for both dorsiflexion and palmar flexion, suggesting that dynamic traction splint by artificial muscle may be an effective splint for the management of wrist joint contractures.

Keywords: dart-throwing motion, Dynamic Traction Splint by Artificial Muscle, range of motion, splint, wrist joint contracture

Introduction

In treating fractures near the wrist joint, long-term protective fixation or inadequate treatment may cause joint contraction, limiting the range of motion (ROM) of the wrist's palmar and dorsal flexion (Orisaka et al., 2016). Wrist joint movement comprises the sum of the movements of the carpometacarpal joint (C-L joint) and the radiocarpal joint (Koji and Koichi, 2005). The ratio of the movement of these two joints to that of the entire wrist joint is called the contribution ratio, and this needs to return to normal to improve wrist movement. To prevent and improve contractures at an early stage, it is desirable to perform rehabilitation that effectively exercises each joint depending on the case (Masaaki et al., 2003). In rehabilitation, it is important to improve the movement restrictions of each joint and normalize the contribution ratio (Koji and Koichi, 2005; Kotarou, 1987; Masaaki et al., 2003), which has traditionally been analyzed using two orthogonal axes of rotation: flexion-extension and radial-ulnar deviation (Volz et al., 1980).

However, recent studies have reported that while performing many activities of daily living (ADL), the wrist articulates an oblique axis defined by the dart-throwing motion (DTM). The DTM is predominantly the result of midcarpal joint movement (Kenji et al., 2003; Shinsuke, 2016; Werner et al., 2004). This suggests that motion in the DTM plane can be preserved following wrist surgery, such as radiocarpal fusion, provided midcarpal motion is permitted (Arimitsu et al., 2009; Calfee et al., 2008; Moritomo et al., 2014). DTM has been shown to allow minimal relative rotation of the scaphoid and lunate (Crisco et al., 2005; Edirisinghe et al., 2014; Moritomo et al., 2014; Werner et al., 2004); hence, it may be permitted during early mobilization following injury. However, an accurate measurement of DTM is required before it is used in clinical practice because deviation from the DTM path reportedly increases the relative motion of the carpal bones (Crisco et al., 2005). Moreover, the development and clinical effects of dynamic splints involving DTM should be considered (Colditz, 1996; Braidotti et al., 2015). However, these splints must be composed of rigid materials to enable active movements, making them difficult to use when treating a condition such as a contracture requiring tissue expansion.

Therefore, based on a dynamic splint that has a clinical effect on wrist joint contractures (Feehan and Fraser, 2016), we devised a new orthodontic splint that combines DTM and the traction effect, thereby addressing common problems. The developed splint, the Dynamic Traction Splint by Artificial Muscle (DTSaM) (Nakayama, 2020; Nakayama et al., 2020), is an artificial muscle-type traction splint for exercising the wrist joint that incorporates a pneumatic artificial muscle (PAM) as the power source of the straightening part to achieve traction at the wrist and effective passive motion (DTM). Regarding the exertion of tension, the PAM is superior to the rubber band, which is the source of power in conventional dynamic orthoses. DTSaM also functions as a serial progressive splint that gradually corrects the shape according to the target using artificial muscles.

The development of DTSaM will enable approaches to treat cases of wrist contraction with limited C-L joints and cases of distal radius fractures and carpal fractures. As a result, we hypothesized that the treatment period would be shortened, and the treatment outcomes would be improved using DTSaM. To test this hypothesis, it is necessary to examine the therapeutic effect of contracted hands after a certain period post-onset. Therefore, the purpose of this study was to investigate the therapeutic effect of DTSaM in patients with wrist joint contractures.

Structure and characteristics of the DTSaM

Features and mounting diagrams of McKibben artificial muscles are shown in Fig 1. The DTSaM includes the controller, palm finger cuff (2), wrist cuff, forearm cuff (Dia Kogyo, Okayama, Japan), dorsal stay (1), McKibben artificial muscles (two palms, dorsal), elbow joint, and forearm fixtures (Orfit thermoplastic material, self-made) (Fig 2). The primary feature of this splint was the use of PAM to correct dorsiflexion and palmar flexion while exerting traction. The PAM was structured such that the rubber tube was constrained by the elastic material in the longitudinal direction of the finger. Hence, the rubber tube expanded toward the center point and contracted when pressurized (Fig 3).

Regarding the angle of palmar flexion, the finger cuff for flexion was attached to the middle and ring fingers while the wrist cuff was attached. The finger cuff and PAM were attached, and an artificial muscle was attached from the finger cuff to the lateral epicondyle of the humerus. As the PAM contracted, palmar flexion movement was performed, and the DTM was reproduced (Fig 3A).

The artificial muscle expanded in the direction of dorsiflexion, as shown in Fig 3B, and the dorsal stay of the wrist joint restricted movement of the carpal bone and pressed the carpal bone in the volar direction. Traction was then added to the metacarpal bone, and traction and dorsiflexion of the wrist joint were performed. The traction method is very different from that of a conventional wrist-traction device. To reproduce the DTM, the PAM was attached, and traction was performed to enable dorsiflexion motion.

Case reports

Four hands of three patients were assessed after the diagnosis of wrist joint contracture at our clinic. The patients were all female, with an average age of 70.5 years. The occupational therapist in charge installed the splint, and the average splint usage period was 5 weeks. One patient had a fracture of the distal radius in one hand, another had a Galeazzi fracture in one hand, while the third patient had pyogenic tenosynovitis in both hands. The wrist joint ROM and grip strength were evaluated initially and after 5 weeks. The wrist joint ROM was evaluated over an average period of 6 weeks. PAM was used to assist in the finishing of the splint.

The splints were required to be worn four times a day for 30 min (in the morning, at noon, after bathing, and before bedtime). The traction force was initiated at 300 kPa and appropriately altered based on patients' symptoms. Informed consent was obtained from all study participants. The study was approved by the Kansai University of Social Welfare Ethics Committee (approval number: 19-16).

Case 1 (Fig 4)

Introduction: The DTSaM was fitted to a patient with residual pain and limited ROM after a distal radius fracture. As a result, the pain was reduced, and the ROM improved.

Patient information: A woman in her 70s with a distal radius fracture. The patient had previously fallen and sustained an injury while bathing at the facility. On the same day, she visited hospital "A" and underwent open reduction internal fixation. At 1 year postoperatively, pain persisted. Therefore, she visited hospital "B," and an artificial muscle splint was implemented on the next day as per the doctor's recommendation.

Primary concerns and symptoms of the patient: The main complaints were limited ROM of the wrist joint and wrist pain during ADL.

Assessment method and result: The initial range of joint motion measured by a wrist goniometer (Sakai Medical Co., Ltd., Tokyo, Japan) was 20° for palmar flexion and 15° for dorsiflexion. The grip strength was 5 kg. The range of joint motion after 5 weeks was 45° for palmar flexion and 45° for dorsiflexion (Table 1). The ROM of palmar flexion and dorsiflexion improved by 25° and 30°, respectively, from the start to 5 weeks. Grip strength recovered to 77% of that on the healthy side (Table 2). Improvements occurred without any problems.

Therapeutic intervention: Active ROM training was initiated from the day after the diagnosis while paying attention to the exacerbation of pain. After receiving permission from the doctor, a DTSaM was worn to reduce pain and improve the ROM. The splint was fitted after confirming the color tone and subjective symptoms of the fingertips for 3 min after wearing the wrist joint cuff (Volz et al., 1980) so as not to impair blood flow or increase pain. From the first week after diagnosis, DTM training was mainly performed in an overflow bath with mild passive exercise. The traction force was changed to 400 kPa from the second week after diagnosis. At 4 weeks after the diagnosis, light-duty work activities were started, and only movements requiring force were restricted. The traction force was set to 400 kPa in the correction direction. As the pain was alleviated from the fifth week, heavy-duty work was started, and all restrictions on activities such as gripping heavy bicycles were lifted. The DTSaM was also completed.

Strengths of the approach: Artificial muscle coercion was adjusted according to the pain.

Case 2 (Fig 5)

Introduction: When admitted to the facility, the patient experienced severe wrist joint pain while eating and changing clothes, which was a major obstacle to ADL. The pain was significantly reduced following DTSaM attachment.

Patient information: A woman in her 80s with a Galeazzi fracture. She fell and was injured while taking a bath at a low-cost nursing home. On the same day, she visited hospital "A" and underwent open reduction internal fixation. The pain persisted at 1 postoperative year. Therefore, she visited hospital "B," and an artificial muscle splint was implemented on the next day as per the doctor's recommendations.

Primary concerns and symptoms of the patient: When using chopsticks and spoons and changing clothes, the patient experienced intense pain in the wrist joint, and assistance was required.

Assessment method and result: The ROM at the start was 25° for palmar flexion and 25° for dorsiflexion. Pain during exercise was recorded as 5 cm on a visual analog scale (VAS). The patients' grip strength was 5 kg. The ROM of the joints after 5 weeks was 45° for palmar flexion and 55° for dorsiflexion (Table 1). VAS improved to 1.5 cm. The ROM of wrist flexion and dorsiflexion was 20° and 30° dorsiflexion from the start to 5 weeks. VAS was reduced to 1.5 cm, and grip strength recovered to 69.2% of the healthy side (Table 2). As a result, the patient confirmed that the tension was relieved and the pain had stopped, and eating and their ability to operate a wheelbarrow improved without any problems.

Therapeutic intervention: Active ROM training was initiated from the day after the diagnosis while paying attention to the exacerbation of pain. After permission from the doctor, the DTSaM was worn to reduce pain and improve the ROM. From the first week after diagnosis, DTM training was mainly performed in an overflow bath with mild passive exercise. From the second week after diagnosis, tendon gliding training, active pinch training using equipment, and ADL training were started. In addition, the traction force was increased to 400 kPa. However, although the palmar flexion angle was improved, dorsiflexion restriction remained, the change in grip strength was small, and the pain felt in the flexor carpi ulnaris remained strong. Therefore, when the DTSaM was not worn, both the artificial muscle of the DTSaM and the wrist joint cuff were removed, and instructions were given to use a simple sprint to stabilize the distal radial and radial carpal joints. In addition, as the dynamic tenodesis effect was positive, a low-load resistance training was initiated with a traction force of 200 kPa for gliding training and strength training of the flexor and extensor tendons.

At 4 weeks after the injury, light-duty work activities were started, and only movements requiring great force were restricted. The traction force was set to 400 kPa in the correction direction and 250 kPa in the resistance movement. Although the dynamic tenodesis effect was negative, the simplified sprint remained continuously attached. Because pain was alleviated from the fifth week, heavy work was initiated, and restrictions on ADL were lifted. The DTSaM was also completed.

Strengths in the approach: DTSaM could be used in combination with resistance training using artificial muscles and a simple splint for resting by removing the cuff from the wrist joint.

Case 3 (Fig 6)

Introduction: As a result of index finger tendonitis, the wrist joint ROM itself was restricted, but the ROM was significantly improved using the DTSaM.

Patient information: A woman in her 60s with pyogenic flexor tenosynovitis. She experienced pain in her right index finger without any apparent reason, and movement was gradually lost. A joint injection was administered at clinic "A," and the pain stopped. However, the wrist and

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shoulder joints stopped moving, and the ROM did not improve. Subsequently, a specialist outpatient consultation was conducted, and therapy was started at hospital "B" with a new splint.

Primary concerns and symptoms of the patient: The wrist joint and finger ROMs were restricted, and both movements related to ADL and activities parallel to daily living were hindered.

Assessment method and result: At the start, the ROM (right/left) of palmar flexion and dorsiflexion was 25/20° and 10/15°, respectively, and grip strength was 5 kg. The range of joint motion after 5 weeks was 45/40° for palmar flexion and 45/40° for dorsiflexion (Table 1). The ROM of palmar flexion and dorsiflexion from the start to 5 weeks was 20/30° of palmar flexion and 20/30°. Grip strength recovered to 69.2% of that on the healthy side (Table 2). ADLs relating to living and shopping were also improved without any problems.

Therapeutic intervention: From the day after the diagnosis, automatic and passive ROM training was started while paying attention to the exacerbation of pain. After permission from the doctor, the DTSaM was worn to reduce pain and improve the ROM. From the first week after diagnosis, DTM training was mainly performed using an overflow bath and passive exercise. The patient was instructed to start light-duty work activities and limit the movements requiring great force. From the second week after the diagnosis, tendon gliding training, active pinch training using equipment, and ADL training were started. In addition, the traction force was increased to 400 kPa. However, although the palmar flexion angle improved, the dorsiflexion limitation remained. Therefore, during the daytime, traction and dorsiflexion were provided by wearing a guidance device that controlled the movement of the DTSaM in the palmar flexion direction. As the pain was alleviated from the fifth week, heavy work was started, and all restrictions such as touching hands and grasping heavy objects were lifted. The DTSaM was also completed.

Strengths and limitations in the approach: This orthosis could be approached by selecting traction or DTM exercise according to the limiting factors.

Discussion

We devised and investigated the therapeutic effect of a new splint, DTSaM, that can stretch tissues using a highly flexible clothing material and PAM, in three patients (four hands) with wrist joint contractures. Our results suggest that DTSaM may be an effective splint for the management of wrist joint contractures.

The mean (±standard deviation) angle of palmar flexion was 21.3° (±5.4) initially and 43.8 (±9.7) at 5 weeks; the improvement in the angle from the start was 22.5°. The mean angle of dorsal flexion improved from 16.3° (±4.4) at the start to 45.0° (±6.9) at 5 weeks; the improvement in the angle from the start was 28.7 °. The grip strength improved from 15.7% of the initial healthy side at the start to 72.5% at 5 weeks. In a study conducted by Jongs et al. (2012), 40 patients with wrist joint contractures after a distal radius fracture were divided into control and experimental groups and were followed up for 12 weeks. The control group received care comprising exercises and advice. The experimental group received a dynamic splint that extended the wrist. In the control group, the improvement in the angle of the wrist joint's dorsal flexion was 10°, and that of the palmar flexion direction was 11°, from the start to 12 weeks. In the experimental group, the improvement in the angle of the dorsal flexion of the wrist joint was 9°, and that of the palmar flexion was 11° from the start to 12 weeks. Compared with the results of this study, the treatment period was significantly shorter, and the ROM of palm flexion and dorsiflexion was greatly improved.

Wrist joint contractures are known to be susceptible to C-L joint limitation (Lucado and Li, 2009). The C-L joint is highly affected by the angle of dorsiflexion (Crisco et al., 2005); therefore, patients with wrist joint contractures have a restricted dorsiflexion ROM. Kay et al. (2008) reported the importance of hand therapy after removing pins and/or casts. The exercise program was progressive and consisted of active ROM exercises from week 3. The control group did not receive any physiotherapy interventions. The angle of dorsiflexion improved from 30° to 55°, while that of the palmar flexion angle improved from 31° to 47°. Meanwhile, the control group showed an improvement in the dorsiflexion angle from 41° to 60°, while that of palmar flexion was from 31° to 47°. The present results were almost the same as those associated with the rehabilitation reported in the study by Kay et al. (2008) for dorsiflexion and palmar flexion. Thus, it is presumed that DTSaM is also pertinent to the C-L joint. These results suggest that DTSaM may be an effective splint for the management of wrist joint contractures.

A traditional Dart-Splint may be utilized in postoperative rehabilitation protocols wherein it is necessary to immobilize the radio-carpal joint, such as following surgical repair or reconstruction of radio-carpal ligaments, scapholunate ligaments, midcarpal instability, and radioscapholunate fusion. Moreover, the Dart-Splint can also be recommended for the conservative treatment of several types of predynamic and dynamic scapholunate interosseous ligament instability and palmar midcarpal instability (Braidotti et al., 2015). These orthoses must be rigid orthotics and should be focused on active motion. Therefore, they are difficult to apply to cases such as contractures that require tissue expansion (Braidotti et al., 2015). Therefore, we incorporated artificial muscles into the correction function and devised a new splint (DTSaM) that reproduced the DTM.

Generally, PAM enables effective treatment to be delivered under conditions of relatively low pressure and reduced tension and provides powered torque to the DTSaM splint. Additionally, its utilization enables the use of a flexible, lightweight, easily maintained, and inexpensive splint. Recent studies have quantified the force-length, force-velocity, force-activation, and bandwidth properties of artificial pneumatic muscles in detail (Davis et al., 2003; Klute and Hannaford, 2000; Klute et al., 2002; Reynolds et al., 2003). PAM, which can exert a strong power with weak pressure, is well suited for mimicking natural gait movement (Klute and Hannaford, 2000; Klute et al., 2002) and, in the current splint, provides a power-assisted glove (Stewart, 1991).

It is considered that this splint improved the ROM of palmar flexion, which greatly contributes to the C-L joint, by improving the mobility control of the C-L joint through the incorporation of the DTM function. Furthermore, as the dorsiflexion movement had also improved as compared to that in previous studies (Jongs et al., 2012; Kay et al., 2008), the radiocarpal joint's momentum may be increased, and traction may be possible. In addition, by using artificial muscles, it is possible to gradually modify the shape according to the patients' needs; therefore, it is presumed that the function of serial progressive splints is also improved from the previous research. In particular, Lucado and Li (2009) showed clinically important gains in the passive motion range using serial progressive splints.

This study had several limitations. First, it only included a limited number of cases that were non-uniform regarding the patient injury/disease. Second, the splint installation confirmation at home was verbal only, without a checklist. Third, the only evaluation items were the ROM and grip strength measurements. Therefore, the evaluation results alone are insufficient to demonstrate the effects of wearing the splint. Future research should compare outcomes with conventional splints and evaluate the inter-examiner reliability regarding the comfort and ease of wearing this splint.

In conclusion, we investigated DTSaM in three patients with wrist joint contractures and four hands and examined the effect of sprint based on the results. We found that the wearing effect of the DTSaM was better than that found in a previous study (Jongs et al., 2012; Kay et al., 2008). It is considered that this splint improves the ROM of palmar flexion, which greatly contributes to the C-L joint by improving the mobility control of the C-L joint through the incorporation of the DTM function. Furthermore, as the dorsiflexion movement was improved, the radiocarpal joint's momentum may be increased, and traction may be possible. In future studies, it will be necessary to apply DTSaM not only in patients with wrist joint contractures but also in patients with postoperative wrist joint disease, for shortening the treatment period and improving QOL.

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Tables

Table 1. Evaluation results at the start and after 5 weeks in the three cases

Case	Diagnosis	Start ROM (active palmar flexion/dorsiflexion) (°)	Final ROM (°)	Duration of wearing the splint (weeks)	Improvement in ROM (°)
1	Distal radius fracture	15/20	45/45	5 weeks	30/25
2	Galeazzi fracture	25/25	45/55	5 weeks	20/30
3	Pyogenic flexor tenosynovitis	Right 25/10	45/40	5 weeks	20/30
		Left 20/10	40/40		20/30

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Table 2. Average measured values for each endpoint

Evaluation	Start of the splint treatment	After 5 weeks	Improvement rate
Grip strength	15.70%	72.50%	56.8%
Palmar flexion	21.3±5.4	43.8±9.7	22.5%
Dorsiflexion	16.3±4.4	45±6.9	28.7%

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Figure Legends

Fig 1 Structure of the McKibben artificial muscle

When pressurized, the left and right diameters contract and the upper and lower diameters expand. The expanding force is used to correct the splint.

Fig 2 Components of the DTSaM

① Forearm cuff (Daiya Industry Co., Ltd., Okayama, Japan), ② handcuff (Daiya Industry Co., Ltd., Okayama, Japan), ③ artificial muscle for palmar flexion (×2), ④ artificial muscle for dorsiflexion (×2), and ⑤ controller.

Fig 3 Mechanism of the wrist's palmar flexion and dorsiflexion
A: Regarding the direction of palmar flexion, the finger cuff for flexion is attached to the middle finger and the ring finger while the wrist cuff is attached. The finger cuff and PAM are adhered and attached the other to the lateral epicondyle of the humerus. As the PAM contracts, the palmar flexion movement is performed, and the DTM is reproduced.

B: The artificial muscle expands, and the dorsal stay of the wrist joint restricts the movement of the carpal bone and presses the carpal bone in the volar direction. Thereby, traction is added to the metacarpal bone, and traction and dorsiflexion of the wrist joint are enabled.

Fig 4 Range of motion (ROM) improvement in Case 1

A: Wrist dorsiflexion ROM when the splint is worn. B: ROM of wrist flexion when wearing the splint. C: Wrist dorsiflexion ROM at 5 weeks after splint use. D: Wrist palmar flexion ROM at 5 weeks after splint use.

Fig 5 Range of motion (ROM) improvement in Case 2

A: Wrist dorsiflexion ROM when the splint is worn. B: ROM of wrist flexion when wearing the splint. C: Wrist dorsiflexion ROM at 5 weeks after splint use. D: Wrist palmar flexion ROM at 5 weeks after splint use.

Fig 6 Range of motion (ROM) transition in Case 3

A: Wrist dorsiflexion ROM when the splint is worn. B: ROM of wrist flexion when wearing the splint. C: Wrist dorsiflexion ROM at 5 weeks after splint use. D: Wrist palmar flexion ROM at 5 weeks after splint use.