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Research article

An optimal de Quervain's tenosynovitis splint with ergonomic thumb support and evenly distributed pressure

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ABSTRACT

Splinting is a conventional treatment for de Quervain's tenosynovitis (dQt). However, existing splints have problems such as excessive thermal discomfort and poor fit, which have been pointed out in previous studies. This study proposes a new functional splint consisting of both hard and soft materials with the aim of providing wear comfort with a good fit and sufficient stability of the injured hand. Thumb support of the splint is an important component that controls and protects the affected thumb. To develop an ergonomically shaped thumb support, 16 participants with dQt were recruited for three-dimensional (3D) scanning of their hands. The angles of the wrist and the curvature of the thumb were measured using computer software, and the results were used as a reference for the design of the prototype supports. Excessive pressure on particular regions, such as bony areas, may cause discomfort or pain. To ensure the wear comfort of the proposed splint, a finite element model (FEM) was built to simulate the wear process of the splint and hence to predict the pressure distribution exerted from the splint onto the hand of the wearer. The simulated results show that the pressure is evenly distributed over the hand, indicating that patients are likely to wear the proposed splint comfortably during their treatment period.

1. Introduction

Repetitive hand movements are commonly required in different occupations, such as pianists, secretaries, garment workers, gardeners, and construction workers. Playing musical instruments, using a computer mouse and keyboard, trimming plants with heavy tools, and putting in screws require forceful pinch grips, repetitive thumb and finger motions, or twisting of the wrist. These movements may lead to a hand disorder called de Quervain's tenosynovitis (dQt) [1]. dQt is a painful condition involving inflammation of the synovial sheaths of the abductor pollicis longus (APL) and extensor pollicis brevis (EPB) tendons in the first dorsal compartment [2]. Patients with dQt usually experience pain, soreness, and tenderness along the radial side of their hand [3,4]. A higher prevalence of dQt has been found in women [5] and in those aged 40–60 years [6]. With the rapid development of technology, the potential risk of dQt in young adults increases with the increased use of smart devices, such as smartphones and tablets [7].

Splinting is a conventional and noninvasive treatment for patients with dQt, particularly those with mild symptoms. The purpose of splinting is to stabilise and protect the affected hand. Long and short splints are the two main types used for dQt. The former is usually made of thermoplastic materials, whereas the latter is made of flexible materials such as neoprene fabrics. Because the long splint is

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made of rigid materials with limited ease of wearing, some patients point out that the splint causes pain in the protruding areas due to fit issues and the rigidity of the splint [8]. They also note the bulkiness and thermal discomfort caused by the splints [9]. For short splints composed of flexible materials, the ability to control hand movement during use remains ambiguous. In this case, a splint that is composed of both hard and soft materials can be the solution, which can accommodate different hand shapes with a good fit, provide wear comfort and offer sufficient control over hand movements.

A problem associated with long splints is the pain caused by the hardness of the material. Therefore, a finite element analysis (FEA) can be used to investigate the exertion of pressure from the splint to the hand of the wearer. Finite element models (FEMs) have been developed in the literature that are related to examining the splinting process. Cazon et al. built finite FEMs to compare the stress and displacement of two different splints with four wrist motions [10]. Hua et al. developed FEMs to investigate stress distribution in soft tissues using three types of splints for treating distal radius fractures [11]. In previous studies, FEMs have mainly investigated the performance of rigid splints, whereas there are fewer studies using FEA for evaluating splints with softer materials.

This study proposes a new functional splint composed of both hard and soft materials for treating dQt. The design concept and development process aim to provide a good fit, comfort, and sufficient control of the injured hand. As the exertion of high pressure on particular regions of the hand causes discomfort, an FEM of the proposed splint was developed to investigate the pressure distribution on the hand during the splint wear process.

2. Methods

The design concept of the proposed splint aims to enhance the wear comfort and fit performance of the splint, while simultaneously maintaining hand stabilisation. The most important part of a splint for treating dQt is the thumb support, which supports the tendons along the radial side of the hand, controls thumb movement, and protects the injured area. To avoid aggravating symptoms owing to inappropriate pressure exertion with a poor fit of the support, the thumb support should be designed according to the ergonomic shape of the hand. In this study, 16 patients were recruited to scan three-dimensional (3D) images of their hands to investigate their hand shape. The thumb support was created based on the measured angles using computer software and then printed using 3D printing technology. The body of the proposed splint was fabricated using different types of fabrics and combined with supports to form the final prototype. To investigate the pressure exerted by the proposed splint on the hand, an FEM of the splint was built to simulate the wear process of the proposed splint and predict the pressure distribution. This study was approved by the Human Subjects Ethics Subcommittee of the Hong Kong Polytechnic University. Written informed consent was obtained from all participants.

2.1. Participant recruitment for 3D scanning of hand

To investigate the ergonomic shape of the hand, particularly the curvature along the radial side of the wrist, 16 female participants with dQt were recruited to take part in the study. The inclusion criteria were as follows: 1) female participants aged 18 years or older and 2) had a positive sign of dQt diagnosed through Finkelstein's test by a professional clinician. The exclusion criteria were as follows: 1) received steroid injections for dQt in the past 3 months and 2) had undergone hand surgery in the past. All participants signed a consent form to demonstrate their understanding of the study contents and their agreement to participate.

2.2. Scanning and measuring metacarpophalangeal joint flexion and wrist angles

According to Ilyas et al. (2007), splints for treating dQt require the wrist to be held in a neutral resting position with the thumb at

Fig. 1. Resting position.

30° of flexion and abduction [12]. Nemati et al. (2017) stated that during the fabrication of an orthosis, the wrist of the patient should be held in a position at approximately 10°–20° of extension, and the thumb can be maintained in radial abduction without discomfort [1]. Wilton (2014) suggested that when fabricating a splint, the wrist should be held with a slight ulnar deviation and the thumb with a slight carpometacarpal (CMC) joint abduction and slight flexion of the metacarpophalangeal (MCP) and interphalangeal (IP) joints [13]. In summary, researchers have indicated that a splint for treating dQt should be fabricated with the patient's hand in a natural resting position. Based on a literature review, the angle degrees of the hand that must be determined to fabricate the splint have not yet been unified and standardised. Some of the angles are usually considered, such as the angles of wrist deviation, flexion, and extension, and the angles of the MCP and IP joints of the thumb.

In this study, the participants were asked to assume the natural resting position with their affected hand (as shown in Fig. 1) with a slight extension of the wrist, which is approximately 10°–20°, according to Nemati et al. (2017) [1]. The 3D images of the hands were captured using an Artec Eva handheld scanner (Fig. 2) [14]. After obtaining 3D images of the patient's hand in the resting position, the angles of the thumb and wrist were measured to develop the supports (Fig. 3). The angles included the angle of MCP joint flexion, the angle between the extension of the radius and carpal portion, and the angle between the extension of the ulna and carpal portion. In addition to the aforementioned angles of the wrist and MCP joint, three angles at six portions along the thumb were measured to optimise the fitting performance of the splint. The details of the measurement procedures are described in the next section.

2.3. Measuring angles of curvatures along radial side of the hand

A thumb support with good fit can be designed based on the curvature of the thumb. Curvature is investigated by measuring the angles at the curved surfaces of different parts of the thumb. Fig. 4 illustrates the steps used to obtain the angles of thumb curvature. First, the scanned hand image was imported into Geomagic to define six regions along the radial side of the hand with cross-sectional curves. The six curves were positioned at the proximal phalanx (PP), MCP joint, metacarpal (MC), CMC, and carpal (C) and radius (R) regions. The PP, MCP, and MC curves at the top of the hand were parallel lines 15 mm apart. The same method was adopted to create the CMC, C, and R curves at the bottom of the hand. Second, a vertical midline was drawn along the thumb to create intersectional points. New cross-sectional curves were drawn perpendicular to the vertical midline based on the locations of the intersectional points. Third, the cross-sectional curve at each portion and the vertical midline were exported and transferred into the SolidWorks software. Subsequently, by zooming into the intersectional point, four straight lines 5 mm in length were drawn from the point. Angles α, β, and θ were then defined and measured. Finally, angle measurements that reflect the curvature at different parts of the thumb were used as references to develop the thumb support. Fig. 5 shows the locations of angles α, β, and θ at the six portions along the radial side of the hand.

Fig. 2. Artec Eva handheld scanner [12].

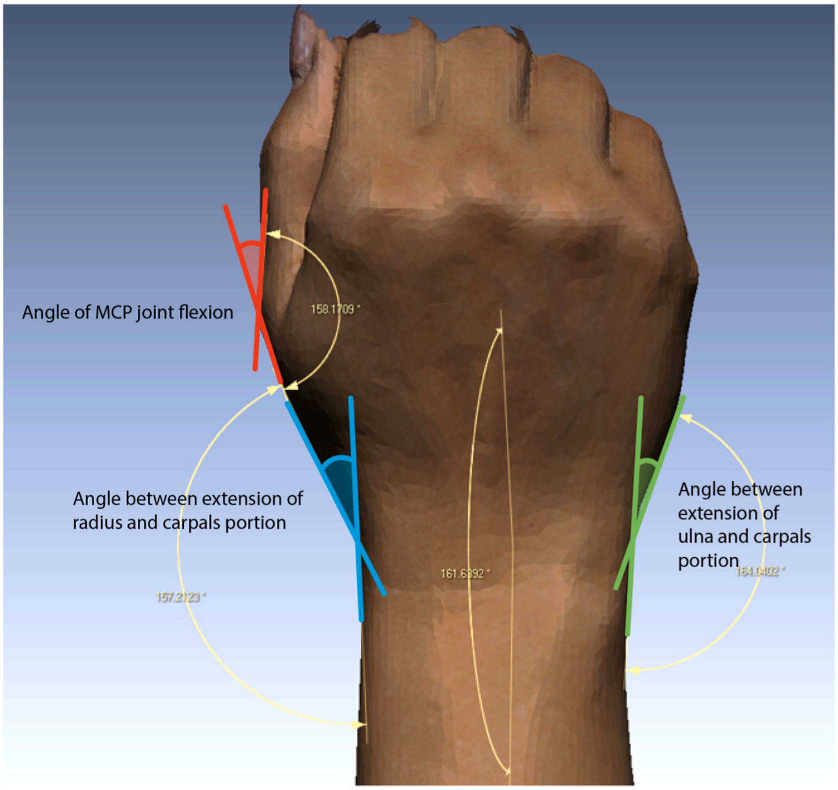

Fig. 3. Locations of the three specific angles.

2.4. Development of FEM

An FEM was developed based on the design concept of the proposed splint. According to Liu and Quek (2013) [15], the two most common shapes of the 3D solid elements that constitute 3D models for solving different field problems are tetrahedrons and hexahedrons. In this study, the element type selected to generate the meshes of the modelled parts was a 10-node linear quadratic tetrahedral element (type C3D10), as shown in Fig. 6, with an element size of 2. Boundary conditions and surface interactions were set to implement the movement of different parts of the model to simulate the wear process of the proposed splint. The FEA results predict the pressure distribution provided by the splint on the skin of the hand.

3. Results

3.1. Design concept of the proposed splint

The proposed splint is composed of both hard and soft materials. The body of the splint comprises radial and ulnar parts and is fabricated using three types of fabrics. A spacer fabric is used for the radial part. The ulnar part is composed of two layers of fabric, of which the outer layer is a satinette fabric and the inner layer is a powernet fabric. Fig. 7 shows the composition of the splint body. Three sets of fastening strips with Velcro tape are sewn onto the top, middle, and bottom parts of the splint. Velcro strips with loops are sewn around the splint body so that wearers can easily attach the strips to create appropriate tightness.

The splint for treating dQt aims to provide support and immobilisation to the affected hand without exerting excessive pressure on the patients. According to Agrawal and Chauhan (2012), normal capillary pressure ranges from 16 mmHg (2.1 kPa) to 33 mmHg (4.4 kPa) [17]. Applying external pressure exceeding 4.4 kPa may hinder smooth blood flow through the blood vessels beneath the skin, leading to anoxia in the surrounding soft tissues and the development of pressure ulcers. To ensure patients can easily determine the appropriate tightness of the splint, the fastening system has two conditions: 1 cm width and 2 cm width. Both conditions underwent pressure tests, with results showing that in the 1 cm width opening, pressure in certain areas of the hand exceeded 4.4 kPa. Conversely, the 2 cm width opening resulted in pressure over the hand being approximately 4.4 kPa or lower. Therefore, based on the pressure test results, it is suggested that patients wear the splint with an approximately 2 cm width opening. Patients should wear the splint comfortably and stop tightening once it achieves a supporting and stabilizing effect with a good fit. Due to the simplicity of the tightening method, patients are able to wear the splint on their own by setting the fastening opening to approximately 2 cm.

The hard components are the thumb and ulnar supports. The two supports are first inserted into the fabricated pockets equipped

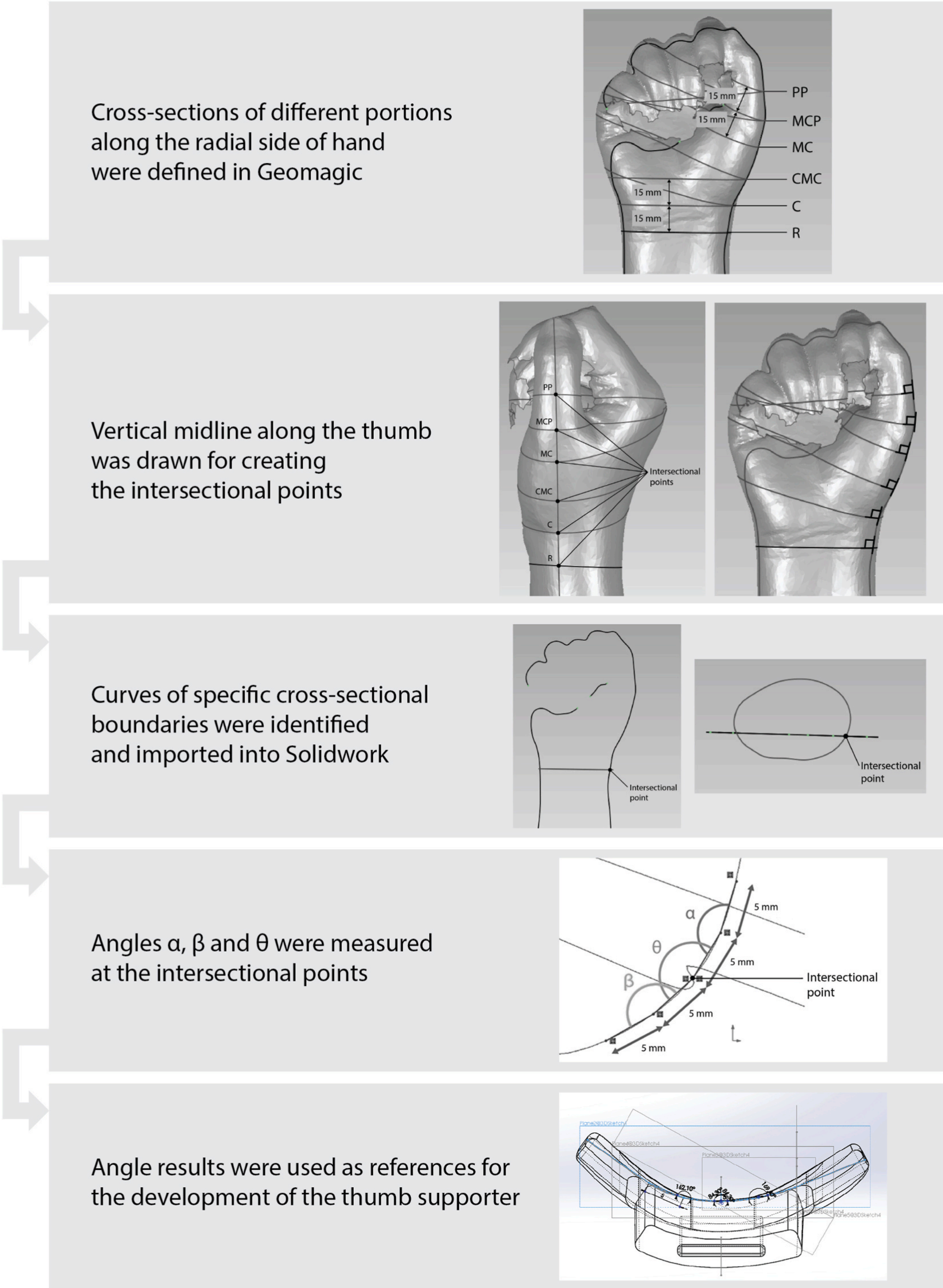

Fig. 4. Steps to measure angles of thumb curvature.

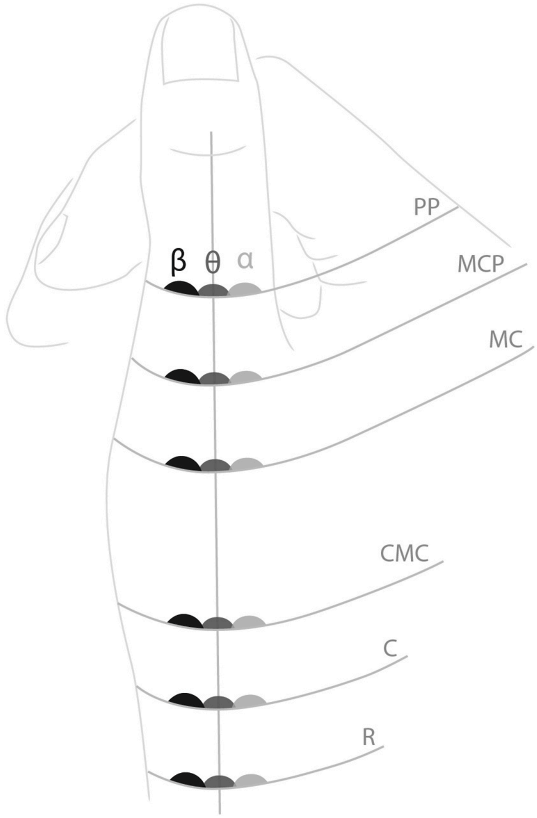

Fig. 5. Locations of angles α, β, and θ at the six portions along the radial side of the hand.

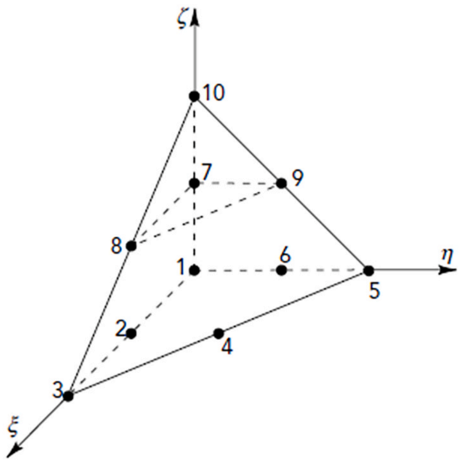

Fig. 6. A 10-mode linear quadratic tetrahedral element (type C3D10) [16].

with Velcro tape with hooks; then, they are attached to the two sides of the hand. During the use of the splint, fastening strips wrap around the supports to secure their positions. The components of the proposed splint are shown in Fig. 8.

3.2. Angle measurements of wrist and curvature of thumb

The ergonomically shaped supports were designed based on the measured angles of the hands of the participants with dQt. The angles of the wrist and the curvature along the radial side of the hand were measured from the 3D scanned hand images using computer software. The mean angles were calculated and are listed in Tables 1 and 2. The angle of the MCP joint flexion was 19°, whereas that at

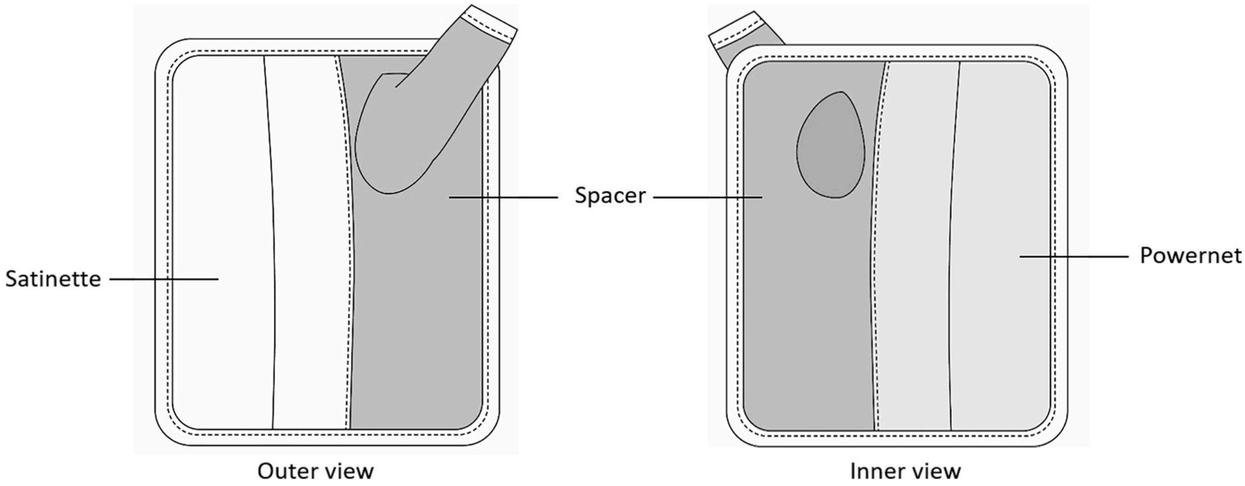

Fig. 7. Composition of body of the proposed splint.

Fig. 8. Components of the proposed splint.

Table 1
Measurements of angle of MCP joint flexion and wrist (mean).

Angle	Degree of angle (S.D.)
Angle of MCP joint flexion	19.0° (7.0)
Angle between extension of radius and carpal portion	19.8° (5.7)
Angle between extension of ulna and carpal portion	19.6° (8.7)

MCP, metacarpophalangeal.

both sides of the wrist was approximately 20°. For the angles of curvature, a larger angle represents a smaller curvature and vice versa. The largest angle of around 172° is angle α at the CMC position, which means that this area has a flatter surface. Angles of approximately 155 °or smaller are found at the PP position, indicating that the skin curvature in that region is higher than that of the other parts of the thumb.

Table 2
Measurements of angles of thumb curvature.

Position	Angle α (S.D.)	Angle θ (S.D.)	Angle β (S.D.)
PP	151.3° (9.4)	155.3° (4.3)	153.0° (5.8)
MCP	159.6° (6.0)	162.5° (4.6)	157.7° (3.9)
MC	171.3° (2.7)	169.7° (6.7)	162.5° (3.7)
CMC	172.1° (6.1),	169.1° (5.1)	163.5° (5.4)
C	169.4° (3.9)	168.6° (5.2)	162.1° (6.1)
R	164.4° (3.8)	162.8° (5.3)	159.8° (5.5)

PP, proximal phalanx; MCP, metacarpophalangeal; MC, metacarpal; CMC, carpometacarpal; C, carpal; R, radius.

3.3. *Thumb and ulnar supports*

The 3D models of the thumb and ulnar supports were created in SolidWorks according to the measured angle results. The inner curved surface of the thumb support matches the thumb curvature, and the angles of the supports match the wrist angles. To accommodate variations in the length of the thumb, a thumb support was designed with the use of 3 separate parts: top, middle, and bottom. The pieces were connected with a piece of metal as the middle trunk. Four different lengths of the middle piece were developed such that, during the use of different combinations, the total length of the thumb support could be adjusted according to the size of the hand. A large hole on the bottom piece was designed to fit the area of the protruding styloid process of the radius, which could prevent excessive pressure being exerted on the bony structure and nearby swollen tissues owing to dQt. The positions of the three support pieces on the radial side of the hand are illustrated in Fig. 9. The 3D printed thumb and ulnar supports are shown in Fig. 10.

3.4. *FEA results*

The FEM aims to simulate the wear process of the proposed splint and evaluate the pressure distribution throughout the hand. The FEM provides a simplified version of the proposed splint and is composed of six modelled parts: the flesh, bone, fabrics of the radial and ulnar sides of the splint, thumb, and ulnar supports (Fig. 11). The fabric strips at the centre of the fabric models represent fastening strips that hold the supports in position. During the simulation, the two edges of the fabric on the dorsal side of the splint moved towards the centre to simulate splint tightening. The predicted stress distribution of the splint fabrics is shown in Fig. 12. In the figure, the regions with higher stress are shown in red, whereas the regions with lower stress are shown in blue. The results show that higher pressure was observed around the wrist and underneath the rigid supports. Furthermore, more stress was observed at the seams of the two types of fabrics in the palm area. In the simulated pressure distribution on the hand surface, denser pressure spots were observed on both sides of the hand (Fig. 13). However, in general, pressure spots are evenly distributed around the hand, and only areas with soft tissues, such as the centre of the palm and parts of the hand that are not covered by the splint, are not subjected to pressure.

4. Discussion

Splints are usually prescribed for patients with mild-to-moderate dQt symptoms. Problems with traditional long and short splints have been observed, such as the hardness of thermoplastics, bulkiness, poor fit, and excessive thermal warmth. Various splint designs have been proposed to address these problems. For instance, Huang et al. (2006) designed a long splint using FEM to optimise the shape, which minimised the amount of thermoplastics used to cover the hand, thereby reducing the weight and enhancing the air ventilation of the splint [9]. Chow (2009) proposed a splint which sandwiches the injured hand between two panels of thermoplastics, thus exposing protruding bony areas, such as the radial styloid process and MCP joint, to air without receiving pressure [8]. Nemati et al. (2017) separated a traditional long splint into two parts, hand and forearm pieces, and joined them with a hinged joint [1]. The presence of the hinged joint allows patients with dQt to flex and extend their wrists but at the same time restricts radial and ulnar deviations of the wrist. Their study showed that patients were more satisfied with the proposed splint than with the traditional splint, as a larger range of hand movements was permitted. Although the aforementioned splints may solve some of these problems, they are all made of rigid thermoplastics. If the splint does not fit the shape of the hand, the patient may experience poor wear. Therefore, this study proposes a new functional splint composed of hard and soft materials. With reference to this design concept, a spacer fabric was applied to the radial side of the hand. The spacer was a knitted fabric with high breathability. The spacer fabric, which comprises monofilaments sandwiched between the top and bottom layers of the knitted structure, can cushion the incoming pressure. Thus, using a spacer fabric along the thumb area can reduce excessive pressure from the rigid thumb support and protect the injured region. Satinette and powernet fabrics are used for the ulnar side of the splint because they are both thin and breathable materials. The former has higher stability, whereas the latter has higher air permeability. The double layers of the two fabrics balance these properties and reinforce the shape of the splint. The stretchability of all three fabrics, that is, the spacer, satinette, and powernet, facilitates a good fit to the shape of the hand. The three pairs of fastening strips provide flexibility in the adjustment of different parts of the hand. A fastening system using Velcro tape is easy and convenient to use; thus, mature or elderly patients can easily donate and doff the proposed splint.

Thumb and ulnar supports offer a good fit if they can accommodate the wrist angles and curvature of the hand. These two supports of the proposed splint were specifically designed and 3D printed using the thermoplastic polymer acrylonitrile butadiene styrene

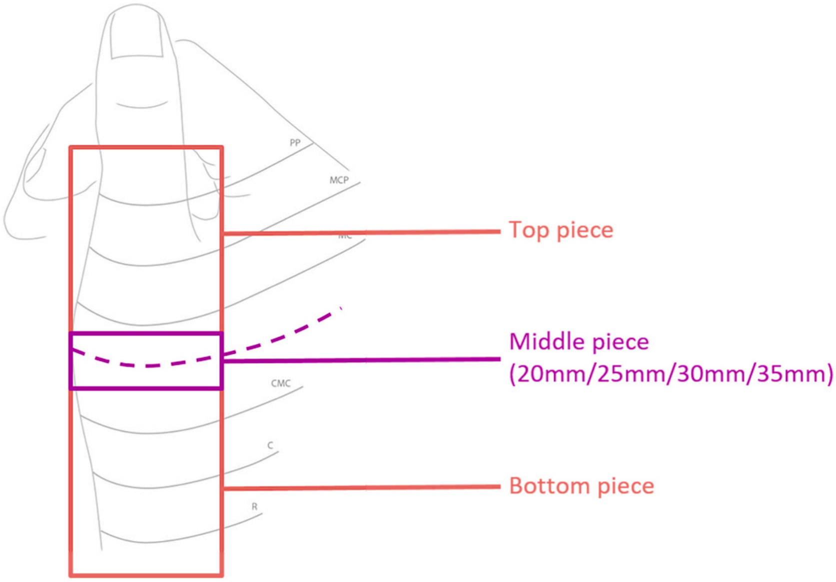

Fig. 9. Positions of the three support pieces at the radial side of the hand.

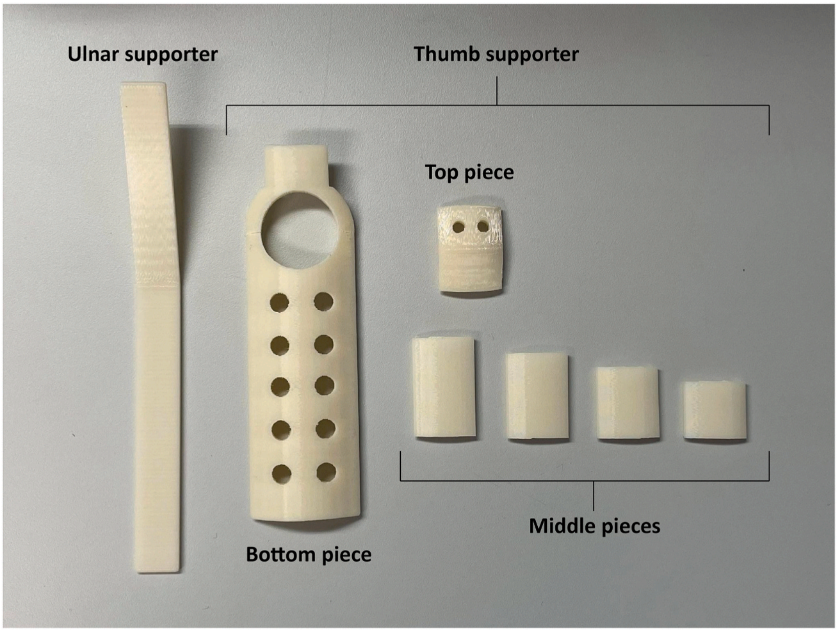

Fig. 10. 3D printed thumb and ulnar supports.

(ABS). Supporters made of ABS are strong enough to control hand movements and support the affected tendons. In the proposed splint, the thumb support is attached along the radial side of the hand, whereas the ulnar support is attached to the ulnar side of the hand. The thumb support can stabilise the thumb, and both supports can control wrist deviation. According to the anatomical structure of the thumb, the APL tendon ends at the first MC bone and the EPB tendon inserts into the dorsal head of the first PP [12]. Therefore, movement of the IP joint is not related to dQt. Furthermore, Nemati et al. (2017) reported that excessive radial and ulnar deviations may lead to dQt, whereas wrist flexion and extension may not significantly affect the two thumb tendons [1]. The proposed thumb support covers the forearm to the first PP so that the IP joint can move without restriction. The attachment of supports on both sides of the wrist restricts the hand from deviating, while allowing a certain degree of wrist flexion and extension. The proposed splint is fabricated with breathable fabrics and equipped with ergonomically designed supports for stabilisation with a reasonable allowance for hand movements, which should offer patients an optimal splint wear experience.

The amount of pressure applied by the splint to the hand could affect the degree of comfort. The splint should be able to stabilise the

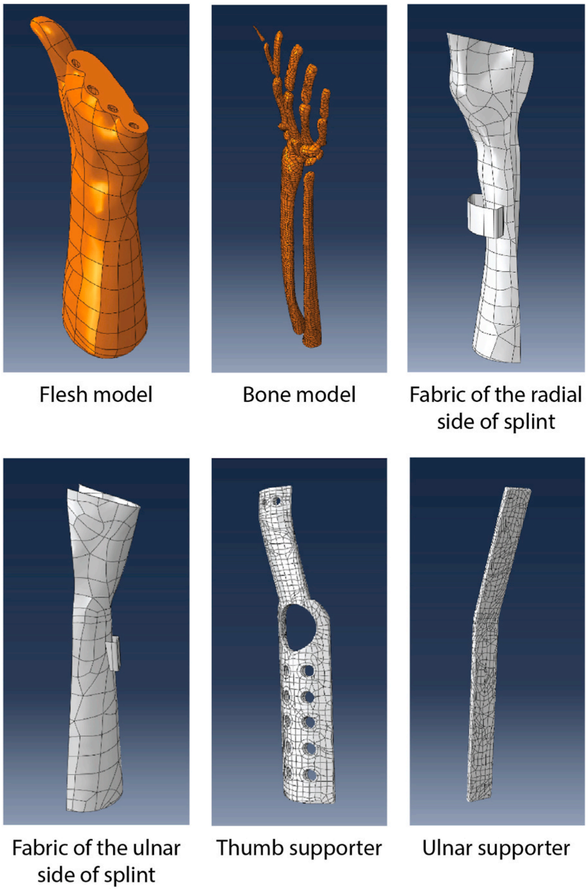

Fig. 11. Six modelled parts in the FEM.

affected hand with an appropriate level of pressure instead of exerting excessive pressure in particular regions, which may cause pain. With the current technologies, the pressure exerted by a garment on the skin of the wearer can be measured using a pressure sensor. However, the measurement area of pressure sensors remains limited. Furthermore, flat pressure sensors may not accommodate the 3D shape of the human hand. Therefore, we recommend the use of FEA to investigate the pressure exerted by the proposed splint. FEA can simulate the splint wear process and predict pressure distribution over the skin of the hand. The results of the splint fabrics showed that more pressure was applied to the wrist areas and two sides of the hand. This result could be due to the presence of strips at the wrist level which hold the supports in place and lead to stress around the wrist. The hardness of the supports may also increase the pressure on the sides of the hand. Another notable point is the presence of a higher stress at the seam of the fabric in the palm area. This indicates that the stitches of the seam must be sufficiently strong to withstand stress during the splint wear process. In the simulated results of the hand model, denser pressure spots were observed in the areas underneath the rigid supports. This finding agrees with the results of pressure on the splint fabrics. In general, the coloured spots indicating low pressure were evenly distributed over the skin of the hand. Thus, patients are likely to wear the proposed splint daily without experiencing discomfort caused by excessive pressure in any particular area.

In vivo experiments are usually conducted to examine the functionality and comfortability of a proposed splint design. However, in this case, we applied a 3-dimensional model to simulate the wearing of the proposed splint. The results showed an even distribution of pressure over the hand. These simulated results are crucial to the development of the proposed splint. During the initial development stage of the proposed splint, performing repetitive investigations of pressure distribution from the splint with model simulation could save both time and cost. Repetitive testing of splint pressure on a patient's hand could be avoided. Since the simulation model shows a desirable result of splint pressure, this indicates that no over-exertion of pressure on particular areas was given by the proposed splint. Therefore, conducting splint intervention can be the next stage of the splint design development.

5. Limitations of the study

This study has three limitations. First, the sample size of the 3D hand images was small. Thus, the generalisation of the angle measurements that reflect the ergonomic shape of the hand in patients with dQt is limited. A larger sample size is recommended for future studies to build a larger database and facilitate the investigation of hand shapes. Second, since the prevalence rate of dQt among

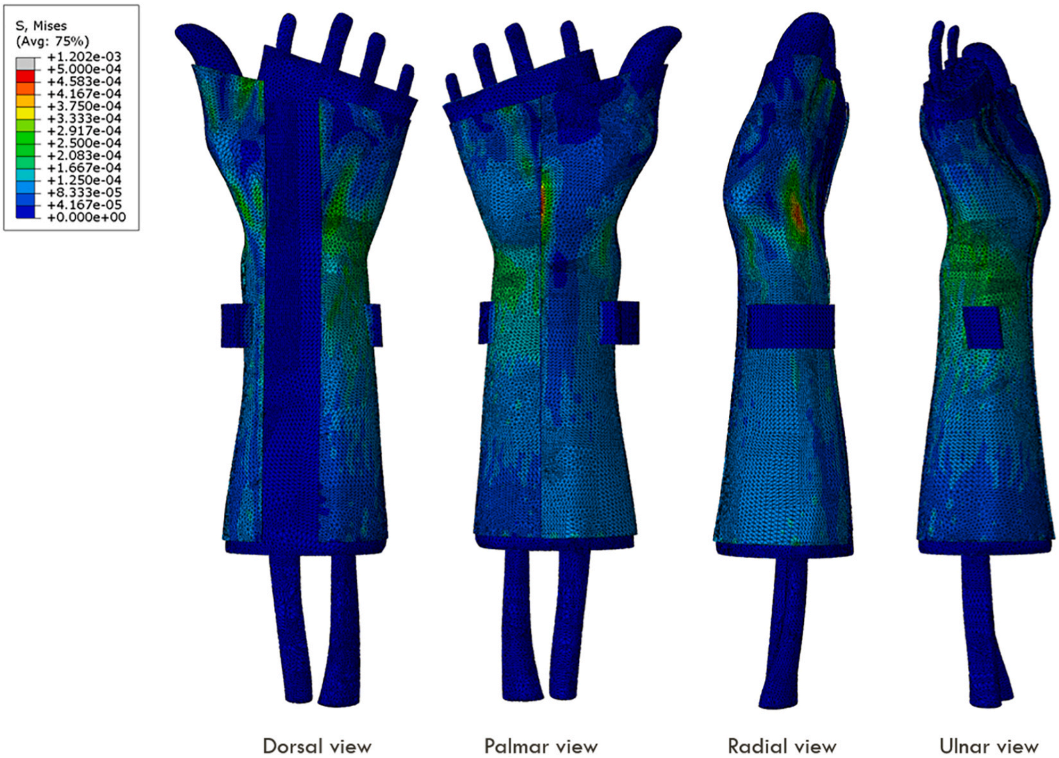

Fig. 12. Predicted stress distribution of splint fabrics.

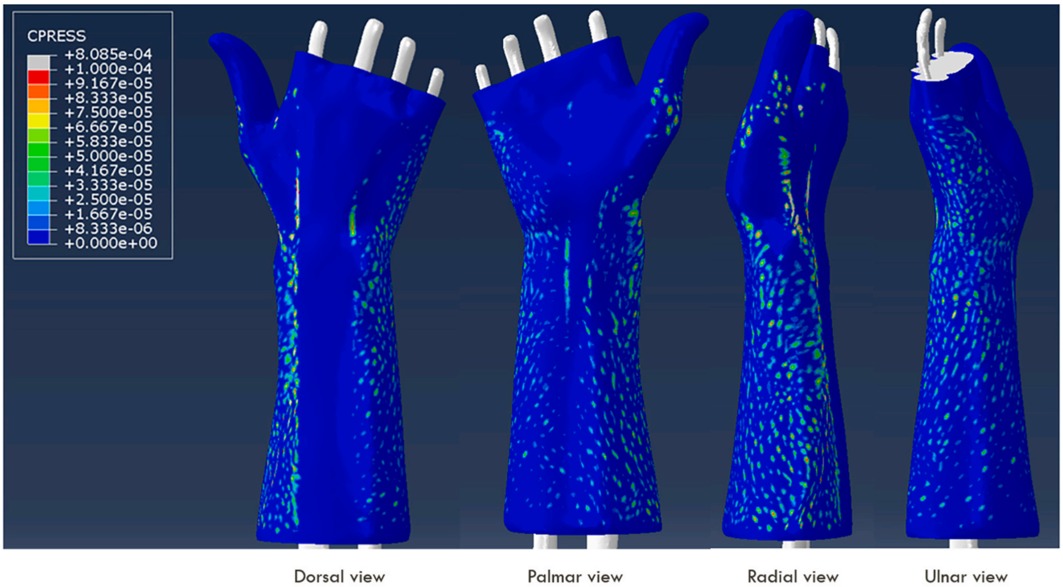

Fig. 13. Simulated pressure distribution on the hand surface.

women is higher than that in men, with around 1.3% of women and only 0.5% of men suffering from this hand disease, this study focused on investigating the splint performances on female patients' hands. It is suggested that repeating the simulation with male hands is necessary for the development of the designed splint, as they have completely different sizes. Third, the FEM developed in this study is a simplified version of the proposed splint. Other anatomical structures, such as tendons and ligaments, and complicated parts of the splint, such as the fastening system, are absent. A more detailed FEM which can model real situations more adequately should be used to predict results with higher accuracy.

6. Conclusion

This study proposes a new functional splint composed of both hard and soft materials for the treatment of patients with dQt. The ergonomic design of the thumb support of the proposed splint was developed based on angle measurements obtained from 3D hand images of patients with dQt. An FEM simulating the wear process of the splint was built to investigate the amount of pressure exerted by the splint on the hand. The results show an evenly distributed pressure pattern over the hand model. Therefore, the splint proposed in this study can provide sufficient comfort yet also offer functionality and can be an alternative option for patients with dQt.

Data availability

The data that has been used is confidential.

CRediT authorship contribution statement

W.S. Tam: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **J. Yip:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **C. Fang:** Writing – review & editing, Validation, Supervision, Funding acquisition. **K.L. Yick:** Writing – review & editing, Supervision, Methodology, Funding acquisition. **S.P. Ng:** Writing – review & editing, Supervision, Methodology, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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