Arrangement of Joint Distraction and Hinge Alignment During Elbow Dynamization Using an Arthrodiatasis Fixator

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Abstract

For the arthrodiatasis technique, a unilaterally hinged fixator is used to treat a post-traumatic elbow. It provides immobilization, distraction, and dynamization to restore elbow functions. An ideal dynamization further necessitates the alignment of both elbow and fixator hinges. This is achieved by the manipulation of a guide pin and fixator joints during the intraoperative and postoperative periods. This study evaluates a method for manipulating the guide pin and fixator joints for elbow dynamization and determines whether the elbow distraction and dynamization are concurrent. Finite element models based on computed tomography images are developed. A detailed discussion about the design and release of fixator hinges is given. The results show that at the distraction stage, the fixator-aided distraction causes the guide pin to shift towards the opposite side. Using this pin-shift effect, the fixator hinge can be shifted to align with the elbow hinge. The ideal value of the initial pin shift is about half the distance activated by the distractor. For ideal dynamization, the release of joints with at least 10 degrees of freedom (DOFs) is necessary to align the elbow and fixator hinges in the sagittal and coronal planes. If both the center locus and hinge jiggle of an articulating elbow are stable, however, only the DOF release of the fixator hinge is necessary after both elbow and fixator hinges are aligned. The distracting force results in the elastic deflection of the elbow-fixator-pin construct, inducing distraction loss and pin shift. The preparation for the pin shift and the estimation of both the center locus and hinge jiggle produces significantly better joint distraction and hinge alignment during elbow dynamization.

Keywords: Elbow, Arthrodiatasis, Stiffness, Distraction, Dynamization

1. Introduction

The primary function of the elbow is to maintain the position of the forearm. The prolonged immobilization of a traumatized elbow often induces adhesion of the periarticular tissues [1-3]. For an orthopedic surgeon, treating an adhered elbow is a complex and challenging therapeutic problem [3-5]. Arthrodiatasis is a surgical technique that uses a hinged external fixator to achieve stabilization, distraction, and dynamization [3-9]. Stabilization enhances the bony union and the subsequent distraction stretches the periarticular tissues to separate the elbow surfaces, thus decreasing the articulating resistance [4,7-9]. Under the proper constraints, dynamization further facilitates the restoration of elbow mobility. From a biomechanical viewpoint, these functions are achieved by manipulating the degrees of freedom (DOFs) of the fixator joints [4-6,8,9].

The two prerequisites for an ideal arthrodiatasis are concentric distraction and hinge alignment [4-11]. Concentric distraction ensures that opposing articulating surfaces are concentrically separated to reduce the mechanical stress on the articular cartilage and to relieve pain during elbow dynamization [4,6,8,9]. Hinge alignment requires that the two hinges of the elbow and fixator be coaxial to avoid motion resistance, internal stress, bone refracture, and implant failure [4,12].

The load-transferring mechanism within the construct is initially driven by the distractor and finally balanced by the periarticular tissues through the fixing pins. The actual amount...
of elbow distraction is highly dependent on the extent of elbow contracture and pin rigidity [13]. During surgery, a pin is usually used as a guide to align both the elbow and fixator hinges before the other fixator components are assembled [4,6,8,10,12,14,15]. For the Orthofix elbow fixator system, the guide pin is suggested to be initially inserted at the proximal border of the trochlea ring structure [14-16]. After distraction, the position of the guide pin is shifted at the elbow center [14-17]. However, there has been no detailed discussion on the value of the pin shift.

The construct forms a close linkage chain system [7]. Consequently, the hinge-aligning ability is a function of the joint DOFs and surgical manipulation. During elbow dynamization, the elbow center is not a stationary point in space and shifts within a locus of approximately 2.5 mm (Fig. 1(a)) [4,9,18,19]. The orientation of the elbow hinge is not fixed in three dimensions (Fig. 1(b)) [4,9,18,19]. The joint’s DOFs should thus be arranged and released to ensure the dynamic alignment of the elbow and fixator hinges. Both the design and the release of the fixator joints are closely related to the hinge alignment of the elbow dynamization. However, few studies have investigated the strategy for joint design and release [7].

This study investigates the pin shift of the concentric distraction and the DOF strategy for the fixator joints during elbow stabilization and dynamization. Bone refracture and implant failure were not investigated. A finite element (FE) model is developed based on computed tomography (CT) images. The effects of the pin shift are evaluated to help the surgical planning of an elbow arthrodiatasis. An optimal arrangement of the joint’s DOFs is expected to lead to smoother dynamization of the bridged elbow. The findings of this study were of significance for fixator bioengineers and orthopedic surgeons.

2. Materials and methods

2.1 Configuration of bridged elbow-fixator model

A 24-year-old male participated in this study. His left elbow was scanned in vivo using a CT imaging system with 1-mm slice separation. The elbow CT images were three-dimensionally reconstructed as triangular meshes using the software PhysiGuide, Version 2.3.1 (Pou Yuen Technology Co., LTD, Changhua, Taiwan). These elbow meshes were further transformed into a solid model with smooth and seamless surfaces using the software SolidWorks, Version 2011 (SolidWorks Corporation, Concord, MA, USA) (Fig. 2(a)). For the periarticular ligaments, the radiolucent property of the fibrous tissue prevents the projective outlines of the ligament boundaries from being exactly defined in each CT slice. The authors thus manually recognized the unclear outlines of ligaments in the images to perform two-dimensional segmentation. Subsequently, the marching cube method was used to reconstruct the three-dimensional configurations of the ligaments in the PhysiGuide environment (Fig. 2(b)). The anatomical shape and attachment sites were visually validated using anatomy references and books [20,21]. There were five ligaments in the elbow models, namely the anterior medial collateral ligament (AMCL), the posterior medial collateral ligament (PMCL), the annular ligament of radius (AL), the radial collateral ligament (RCL), and the lateral ulnar collateral ligament (LUCL) [20,21]. The incline angle between the humerus and the ulnar was assumed to be 120° in the sagittal plane [13].

This study used a unilaterally hinged fixator as an arthrodiatasis device (Fig. 3). On each side, there were one pin clamp, one telescopic joint (1 DOF), one ball joint (3 DOFs), and one rotary unit at the fixator’s center (2 DOFs). The telescopic and ball joints provide axial and rotational adjustment for the fixator center, respectively. The distractor produces the controlled distraction of the bridged elbow during the postoperative period. The cannulated hinge of the rotary unit allows a guide pin to pass through it for aligning the fixator and elbow hinges (Fig. 4(a)).

Fixing pins 5.5 and 4.5 mm in diameter were inserted into the bones and secured by clamps at the humeral and ulnar sides, respectively (Fig. 4(a)). After the pins were fixed, each telescopic joint of the fixator was aligned parallel to the longitudinal axis of the humerus and ulna. A Cartesian coordinate system (X-Y-Z) was established, with its origin at the elbow center, to define the movement of the elbow and the
The mechanical contribution of the cancellous bone was assumed to be negligible and the bones were simulated as cortical shells, their thickness being determined from the CT images. All materials were assumed to be homogeneous, isotropic, and to have linearly elastic properties. For the fixator and bone, the values of Young’s modulus and Poisson’s ratio were respectively estimated to be 200 GPa and 0.3 (316L stainless steel) and 15 GPa and 0.3 (cortical bone) [13,22]. The ligaments were used as the stiffeners of the elbow complex. There have been no previous quantitative reports about the stiffness of adherent elbow joints. Furthermore, detailed data on the material nonlinearity of periarticular ligaments is scarce. Hence, the extent of the stiffened ligament was simply modeled by increasing the Young’s moduli of the healthy ligaments, with linear elasticity [13,23]. The Young’s modulus and Poisson’s ratio of the stiffened ligaments were 118 MPa and 0.49 (AMCL), 97 MPa and 0.49 (PMCL), and 54 MPa and 0.49 (AL, RCL, and LUCL), respectively. The calculated stresses of the fixator and pins were compared with the yielding strength (= 896 MPa) of the 316L cold-worked stainless steel to validate the assumption of linear elasticity.

The humeral head was immobilized and the distractor on the humeral side was activated with constant elongation. Totally, there were six variations of two distraction distances (5 and 10 mm) and three pin shifts (2, 5, and 8 mm). In practice, the distraction distance indicates the elongated span driven by the humeral distractor. The 5- and 10-mm distances were simulated by assigning the Z-directed displacement between the telescopic rod and tube (Fig. 3). This study used the final projective position of the distracted elbow hinge onto the Z-X plane to evaluate the effect of the pin shift. The threads, fillets, and chamfers of the fixing pins and the other minor specifications of the fixator components were omitted to allow simplification of the numerical calculation. The meshes of the construct were generated by an automatic algorithm with the software Simulation Ed. 2011 (SolidWorks Corporation, Concord, MA, USA). The element density of the fixing pins and ligaments was specially controlled to be twice that of the remainder of the model with an overall average element size of 2 mm. This study used the total strain energy as the convergence index of the FE results. The use of 2-mm elements for the bones and fixators and about 1-mm elements were the final results of the convergence evaluation. The mesh refinement was executed for modeling accuracy until excellent monotonic convergence behavior with < 1% difference in the total strain energy was achieved.

The model was meshed with hyperbolic elements to avoid both geometric discontinuities and unrealistically high concentrations of stresses. Using the aspect ratio and Jacobian checks, all ten-node tetrahedral elements were found to be within acceptable distortion limits, thereby maximizing the accuracy of the results. The final meshes consisted of 340,053 elements and 547,677 nodes. The distractor-fixator and humerus-ulna interfaces were simulated with surface-to-surface contact elements without friction. The other interfaces were modeled as perfectly bonded to simulate immobilization.

3. Results

The results of this study can be divided into two parts: pin shift during joint distraction and joint release during elbow dynamization. Figure 5 shows the relative coordinates of the elbow and fixator hinges after distraction. For the 10-mm
distraction, a 5-mm shift of three pin placements produces a final position of the distracted fixator hinge closest to the elbow center (Fig. 5(a)). For the other shifts, the Z-coordinates of the distracted fixator hinge are significantly higher than the X-coordinates. For the 5-mm distraction, the initial pin placement, with a 2-mm shift, can align the elbow and fixator hinges after distraction (Fig. 5(b)). Similarly, the final location of the distracted fixator hinge is further away from the elbow center in the Z- than the X-direction. Figure 6 shows the visual results of different variations of pin shift for the two distraction modes. For the two distraction modes, the ideal value of the pin shift occurs when the initial value of the pin shift is about half the distraction produced by the distractor.

Figure 5. Final coordinates of the elbow and fixator hinges. (a) 10-mm distraction. (b) 5-mm distraction.

Figure 6. Visual demonstration of the pin-shift concept. (a) The elbow within the dashed circle magnified to show the final coordinates of the distracted fixator hinge. (b) 10-mm distraction. (c) 5-mm distraction.

Figure 7 schematically shows the strategy for joint release to achieve hinge alignment during elbow dynamization. For the case of hinge misalignment, there always exist offsets (Δx and Δz) between the projective centers of the elbow and fixator (Figs. 7a(a) and 7b(b)). However, hinge alignment necessitates a coincidence of these two centers, by releasing the ball and telescopic joints. The rotation of the ball joint allows the elimination of the offset Δx (Fig. 7c(c)), whereas elongation of the telescopic joint decreases the value of the offset Δz (Fig. 7d(d)). While the elbow articulates, the movement of the elbow center always necessitates a release of the joint on the humeral and ulnar sides (Figs. 1 and 7e(e)).

4. Discussion

The primary aim of distraction arthroplasty is to provide immobilization, distraction, and dynamization of a post-traumatic joint [4-10,12,14-16]. Whether a hinged fixator can offer a solution to such elbow problems depends on several factors, including the design of the fixator joints, the orthopedic surgical procedure, and the strategy for joint release. Initially, the pins and the fixator joints are fixed to form a rigid linkage for bone union. This is the basic function of a common external fixator. However, the fixator-aided force is necessary to achieve joint distraction. If concentric distraction is desired, the distracting force must be directed orthogonally to the line joining the tips of the olecranon and the coronoid [4,7,9,13]. Further, elbow dynamization can only occur when there is hinge alignment, which reduces internal stress [8,11,14-16]. From a technical viewpoint, the number and release of the joint DOFs should be thoughtfully arranged to accommodate the adjustment of the two hinges over the full range of elbow motion. This study examined how the distraction alters hinge alignment and determined the fundamental requirements for the design and release of the fixator joints.

After fixation, the distracting force internally stretches the periarticular tissues and deflects the fixing pins. Elastic deflection of the fixing pins results in a loss of distraction and hinge misalignment at the elbow center [7,8,13-16]. The distraction loss between the distractor and the elbow is caused by the low rigidity of the pin structure. The fixator and bones are stiffer than the soft tissue and fixing pins. Accordingly, an elastic shift of the fixator hinge occurs after the distraction is activated (Figs. 5 and 6). This is consistent with the recommendations in the Orthofix manual and the literature [7,14-17]. For humeral distraction, the guide pin is recommended to be proximally shifted by half of the value of the distractor-aided displacement. In such a situation, both elbow and fixator hinges are approximately coaxial after distraction. However, it is unclear whether the internally distracted condition pertains during any phase of the elbow dynamization.
In this study, the unilaterally hinged fixator consisted of 10-DOF joints on two sides to allow hinge alignment in the sagittal plane (Figs. 1 and 7). The 6-DOF release of the ball joints compensates for the rotational offsets (Δx) between the projective centers of the elbow and the fixator hinges (Fig. 7(c)). The translational adjustment (Δz) is achieved by releasing two telescopic joints with 2 DOFs (Fig. 7(d)). The rotatory unit provides adjustment of the DOFs to allow hinge alignment in the coronal plane. However, the release, with at least 8 DOFs, inevitably causes dysfunction of the distractors during elbow dynamization. The rotatory unit, with 2 DOFs, must even be released in response to a jiggle of the elbow hinge (Figs. 1 and 7(e)). This indicates that joint distraction and hinge alignment cannot both occur while the bridged elbow articulates. If the hinges can be aligned after distraction and the value of the center locus and hinge jiggle can be neglected (Fig. 1), elbow dynamization can be directly performed without releasing the joints. In practice, this can be done by tightly controlling the pin shift prior to elbow dynamization. However, this was not investigated and represents a limitation of this study. In addition, the DOF release of nearly all joints creates the problem of how to automatically align the elbow and elbow hinges during dynamization. This was not discussed in this study.

5. Conclusion

This study evaluated a method for manipulating the guide pin and fixator joints for elbow dynamization and determined whether the elbow distraction and dynamization are concurrent. The elastic deflection of the elbow-fixator-pin construct shifts the fixator hinge toward the opposite side after distraction. The ideal value of the initial pin shift is about half the distance activated by the distractor. In order to achieve hinge alignment, an arthrodiatasis fixator with at least 10 DOFs is necessary in the sagittal and coronal planes. Theoretically, both joint distraction and hinge alignment is interactive. Careful preparations for the pin shift and the estimation of both center locus and hinge jiggle can significantly improve joint distraction and hinge alignment during elbow dynamization.

References