ABSTRACT
Femur fracture is a frequently occurred injury and usually treated by surgeries. In order to overcome problems involved in the surgeries and improve the surgical operation efficiency, some researches on automated or semi-automated robot-assisted surgery have been carried out. Yet few literature reports on velocity and acceleration planning can be found. In this paper, two algorithms dealing with computation of acceleration are proposed and velocity is computed according to acceleration. The algorithms use information obtained from the surroundings to calculate acceleration. One algorithm evaluates risk of trauma induced by bone fragment motion, and the other one computes acceleration based on the information of reduction path and risk of inducing trauma. From the simulation results, velocity of bone fragment is slowed down reasonably and smoothly when the risk of inducing trauma is high. When the risk falls, meaning that the probability of trauma caused by bone fragment motion is low, moving velocity of bone fragment rises. These results have validated the performance of the proposed algorithms.

KEY WORDS
Robot-assisted surgery, Femur fracture reduction, Acceleration planning, Velocity planning

1. Introduction
Femur fracture is a frequent injury, with the incidence approximately 37 per 100,000 person-years, typically caused by a high-energy injury mechanism in the young or a low-energy mechanism in elderly [1]. However, the surgeons’ treatment of femur fracture, especially the preferred minimally invasive technique of intramedullary nailing, involves many problems such as large amount of radiation exposure to patient and operating staffs with mean duration of X-ray image intensifier 3.6 minutes and average dose of radiation twenty eight millirems [2], and mal-alignment of fracture segments inducing many complications including but not limited to leg-length discrepancy, angular deformity, rotational malunion, delayed union and non-union, and compartment syndrome [3]. In order to overcome these problems, many researchers and physicians are attempting to improve the reduction process and the most promising method is deemed to be the robot-assisted reduction surgery which leads to a considerable reduction in radiation exposure, shorter fluoroscopy times [4] and increased precision of fracture reduction.

Starting from the last decade, much research has been found in the field of robot-assisted surgery of femur fracture. For instance, Leo Joskowicz et al. described a computer-integrated orthopedic system for assisting surgeon in performing closed medullary nailing of long bone fractures. They elaborated the system concept, preoperative modeling, nailing selection, visualization and intraoperative fluoroscopic image processing, and tracking [5]. R. Hofstetter et al. introduced a surgical navigation system [6], based on fluoroscopy images that provide missing information for the procedure of femoral fracture fixation, demonstrating high degree of precision of this technique by an in-vitro study on computer-assisted measurement of femoral antetorsion. T. Hüfner et al. presented a model allowing virtual controlled reduction and providing computer assistance during the fracture reduction. The method of virtual reduction revealed that virtual controlled reduction is nearly as accurate as direct visualization [7]. Gößling T et al. studied intra-operative peak forces and torques during fracture reduction during intramedullary nailing procedure. The maximum resulting force of 411N and the maximum resulting torque of 74N·m were reported. These results could assist the development of reduction techniques and devices [8]. A.E.Graham et al. designed a parallel robot and described the interface including visualization of the fracture, assistance planning and human-robot-interaction [9]. Warisawa et al. also developed a fracture reduction robot with fail-safe mechanism. The robot was mounted to a patient’s foot and provided power assistance to help surgeon to realign fragments [10]. Nevertheless, the robot was only aimed at the nonsurgical management. Several years later after some modification of the robot’s end-effector, their robot connected with pins could be inserted into patient’s bone fragment to assist hip fracture reduction surgery. Koo T.K. et al. developed a reposition device to perform closed
fracture treatment. The device was adjusted off-the-site and reattached back in place to guide the reduction of the fracture fragments. Prototype of the design was a unilateral external fixator [11-13]. However, the system was not designed for automated fracture reduction. Ralf Westphal et al. developed a telemanipulated fracture reduction system consisted of fluoroscopy system, surgical navigation system, commercial serial robot RX90 and control PC [14-15]. Firstly 3D images were acquired and segmented for surface reconstruction so that surface models of fracture fragments were obtained. After computation of target pose and approach direction the fracture reduction could be conducted.

From what has been introduced above, it is evident that the field of robot-assisted femur fracture reduction is promising and fascinating. Great improvement had been achieved in the field since it was proposed. Nevertheless, few research involves the velocity and acceleration planning of femur fracture reduction, although some literature mentioned the necessity of path planning [16]. Precise velocity and acceleration computation of bone fragment is deemed necessary, as it provides safeguard and prevents unexpected collision of two major fragments and collision to arteries and nerves that may prolong convalescence. Reasonable motion planning also makes fracture surgery gentle and tender, alleviates pain, reduces the doses of anesthetics and reduces traumas in the surgery. Besides, it can avoid potential excessive reduction force causing some complications.

In this paper, algorithms for velocity and acceleration computation are proposed. Initial poses of fracture fragments and reduction path are provided pre-operatively by segmentation and surface reconstruction of 3D images and will not be discussed here. Based on the initial poses and realigning path, acceleration planning is determined by two algorithms. One algorithm evaluates risk of trauma induced by moving bone fragment with consideration of surroundings that are filled with soft tissues, nerves and arteries. Another algorithm computes the acceleration of bone fragment with two input parameters, the distance to a destination and the risk of inducing trauma. Finally, motion velocity is computed based on the acceleration.

2. Acceleration and velocity analysis

In femur fracture treatment process, the proximal fragment is held in its position by clinical fixator and the distal fragment is moved to correct anatomic position. Planning of realigning velocity and acceleration is the computation of distal fragment’s motion. Acceleration and velocity analysis discussed in this paper is the determination of their modulus.

2.1 Bone fragment modeling

3D reconstruction of CT images of one femur fracture fragment is shown in Figure 1.

![Fig. 1 Femur fracture fragment](image)

After segmentation and surface reconstruction of 3D images data of fracture fragments, some points are sampled on the fracture surface as shown in Figure 2.

![Fig. 2 Sampled points on the reconstructed fracture surface](image)

Applying least square method to these points, we can find a flat surface that makes the sum of distances between all these sampled points and the flat surface the least. Then the flat surface is offset by enough distance to cover all the sampled points and leave some tolerance between offset surface and sampled points. The flat surface and offset surface are shown in Figure 3. Therefore, bone fragment has been modeled as a regular cylinder with a flat offset surface as shown in Figure 4.
2.2 Computation of acceleration

Motion of distal fragment is denoted by the motion of the center point which is the intersection between fragment axis and offset surface. When approaching to destination, distal fragment should be moved more and more slowly, thereby the distance to the destination, denoted by \( \text{desti\_distance} \), is one parameter to determine acceleration. Critical soft tissues along the reduction path, called obstacles in the paper, are modeled and enclosed by spheres. When distal fragment approaches to these obstacles, it should also be moved slowly. Therefore, in order to determine proper acceleration, we present another parameter, risk of trauma, which is used to evaluate the risk when the distal fragment is approaching to obstacles. The parameter ranges from zero to one and higher value means distal fragment is more likely to collide with the critical soft tissues. To sum up, determination of acceleration is carried out by Algorithm one based on the two parameters, distance to destination and risk of trauma. Scheme of Algorithm one is illustrated as Figure 5.

2.2.1 Algorithm one

Algorithm one computes acceleration based on the two parameters, distance to destination and the risk of trauma. Formula 1 shows the expression for acceleration.

\[
a = \frac{2}{1 + e^{-10w_1}} - 1
\]

\[
w = \frac{c_1}{c_1 + c_2} \cdot \frac{x_1}{x_{1\text{max}}} + \frac{c_2}{c_1 + c_2} \cdot (1 - x_2)
\]

Where, \( a \) means acceleration, \( x_1 \) is \( \text{desti\_distance} \), \( c_1 \) is the weight of \( x_1 \), \( x_2 \) is the risk of trauma, and \( c_2 \) is the weight of \( x_2 \). \( c_2 \) is set to 3 and \( c_1 \) to 1 in this paper. After normalization of \( \text{desti\_distance} \) and risk of trauma, the two normalized parameters are weighted and summed to generate the variable \( w \) containing information of the two parameters. \( w \) is the variable to evaluate the acceleration by expression of acceleration in Formula 1 graphically illustrated by Figure 7.
2.2.2 Algorithm two

Risk of trauma is evaluated by Algorithm two based on three factors: obs_distance, moving_angle, and axis_angle. Formula 2 is proposed to compute the risk.

\[
p = \frac{-1}{1 + e^{-10w+5}} + 1
\]

\[
w = \sum_{i=1}^{3} \left( \frac{k_i}{k_1 + k_2 + k_3} \frac{x_i}{x_{max}} \right)
\]

Where, \( p \) means risk of trauma, \( x_1 \) is denoted as the obs_distance, \( k_1 \) is the weight of \( x_1 \), \( x_2 \) is the moving_angle, \( k_2 \) is the weight of \( x_2 \), \( x_3 \) is the axis_angle, and \( k_3 \) is the weight of \( x_3 \). The weight \( k_1, k_2, \) and \( k_3 \), are set to 1 in this paper. After normalization of the three factors, obs_distance, moving_angle, and axis_angle, the normalized parameters are weighted and summed to generate \( w \) which is the variable to evaluate the risk of trauma by expression of risk in Formula 2 graphically illustrated by Figure 8.

3. Results

Computation of acceleration and velocity is executed in MATLAB. Results of acceleration and velocity show that distal fragment is slowed down smoothly when the risk of trauma is high or distal fragment approaches to destination. When the risk of trauma falls, velocity of distal fragment rises correspondingly.

Figure 9 shows initial poses of fracture fragments whose pose data are acquired by the segmentation and surface reconstruction of 3D images data of fracture fragments. Reduction path is shown by the dash line. There are two obstacles along the reduction path. Obstacle I locates near the beginning of the path and obstacle II is at the location nearby destination.
conspicuous variation of *moving_angle*, as the observed obstacle of distal fragment is switched from obstacle I to obstacle II. The two rising of *moving_angle* show the moving direction of distal fragment is gradually away from obstacle direction. In the Figure 12, there is also a conspicuous variation at the same time of the variation of *moving_angle* because of the same reason that observed obstacle is switched. Before and after the variation, *axis_angle* slumps and then surges showing that axis of distal fragment firstly gradually points at obstacle and then deviates from obstacle.

Figure 13 shows change of risk of trauma. In the Figure 13, there are two peaks of risk because of low values of *obs_distance* and *axis_angle*. Figure 14 is the distance to destination.

Figure 15 & 16 show results of acceleration and velocity of distal fragment. In the Figure 15, the two conspicuous slump of acceleration respond to the two periods of high value of risk. The second of slump of acceleration goes deeper than the first slump, because the distal fragment is more approaching to destination. Velocity reflects well the variation of acceleration. The distal fragment will be moved slowly when the risk is high. When the risk falls, distal fragment will be moved faster again. When distal fragment approaches to destination, motion velocity will once be slowed down.
4. Conclusion

Kinematic analysis of femur fracture fragment, including velocity planning and acceleration planning for fragments realignment, has been proposed. From the results, the velocity is slowed down reasonably when the distal fragment is approaching to destination or the risk of trauma is high. When the risk falls, motion velocity rises again. These results show that the proposed algorithms are suitable for the proposed motion planning with reasonable response to surrounding information and have validated the performance of the proposed algorithms. Applied the algorithms, the motion of bone fragment could be guided and provided safeguard to prevent unexpected collision to critical soft tissues.

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References


