IOP Conf. Series: Materials Science and Engineering **308** (2018) 012010 doi:10.1088/1757-899X/308/1/012010

Integration of computer-assisted fracture reduction system and a hybrid 3-DOF-RPS mechanism for assisting the orthopedic surgery

Irwansyah[*1,2], N P Sinh[1], J Y Lai[1], T Essomba[1], R Asbar[2], P Y Lee[3]

[1]Department of Mechanical Engineering, National Central University, Taoyuan, Taiwan
[2]Department of Mechanical Engineering, Syiah Kuala University, Banda Aceh, Indonesia
[3]Orthopedic Department, Show Chwan Memorial Hospital, Changhua, Taiwan

[*]E-mail: irwansyah@unsyiah.ac.id

Abstract. In this paper, we present study to integrate virtual fracture bone reduction simulation tool with a novel hybrid 3-DOF-RPS external fixator to relocate back bone fragments into their anatomically original position. A 3D model of fractured bone was reconstructed and manipulated using 3D design and modeling software, PhysiGuide. The virtual reduction system was applied to reduce a bilateral femoral shaft fracture type 32-A3. Measurement data from fracture reduction and fixation stages were implemented to manipulate the manipulator pose in patient's clinical case. The experimental result presents that by merging both of those techniques will give more possibilities to reduce virtual bone reduction time, improve facial and shortest healing treatment.

1. Introduction

Utilization the computer-assisted or robotic surgery technology for enhancing orthopedic procedure is still not mature yet. It needs more evident for patients and surgeons to improve the uncertainty and make them sure that those of assisted-technology can provide accurate, predictable and safe treatment. At least two decades research in Computer-Aided Orthopaedic Surgery (CAOS) and Orthopaedic Robotics (CAOR) have happened in design and development level but only a few of them are presently being allowed for clinical trials. In orthopedic clinical practice, complicated bone deformities treatment and unreduced fractures are always problematic issues. In this study, the combination of virtual fracture reduction with a robotic-assisted reduction is proposed to solve those problems. Currently, we have built an integrated preoperative simulation system for orthopedic surgery and have been used as preoperative planning tool for a surgeon to solve clinical cases of bone fracture reduction and implant placement. The system is operated in a PC based environment that integrates the virtual surgery tools in single computer program package, making it easy to implement in clinical applications [1-2]. The aims of our research to study integration of computer-assisted fracture reduction and robotic system. Even though computer-assisted fracture reduction have been developed by several researchers with different level of accuracies, we explore beneficity merging both of cutting-edge-technology. A 3D model of fractured bone is generate directly from a stacks of CT images, segmented in multi region, and virtually reduce and stabilize. A computer-integrated orthopedic system, called FRACAS, was develop for deal with long bone fractures. It replace to use fluoroscopic images to virtual reality display of 3D bone models [3]. A 3D visualization tool was developed to generate a realistic model of the bone-fixator system. The visualization tool has improved the current software to provide a realistic depiction of the treatment procedure [4]. Integrating surgeon instructed, image-guided and robot-assisted applied to reposition long bone fracture. A robotic solution exists to solve the problems of manipulating and reducing long bone fractures [5-6]. Employing 3D imaging and surgical navigation techniques in combination with a robot-assisted reduction procedure to overcome mal-alignment fracture reduction and minimized high x-ray exposures especially for operating team [7]. A new reduction strategy introduced by modification the hexapod computer-assisted fracture reduction system which is detachable, flexible and more precise in coordinate transformations used for closed diaphyseal fracture reduction [8]. A robotic system with 6 d.o.f mobility applied for home positioning of femoral shaft fracture based on Stewart platform [9]. A computer-aided control system might effectively to manipulate external fixators [10]. We outline a system by generating 3D model reconstruction, fracture bone reduction, fragments target coordinate computation, and collecting set of data of rotation and translation fragments displacement to control robot manipulator movement. Then, every single stage of planning reduction simulation and path tracking fracture fragments reduction were presented.

2. Computer-Assisted Fracture Reduction (CAFR)

Reconstruction bone anatomic structure in 3D space is important stages in virtual preoperative planning. Image acquisition, segmentation, virtual fracture reduction and fixation are the virtual surgery simulation features. Focusing on the fracture reduction, the aiming is to position, align the fracture bones and stabilize them into the bone structure. In a simple case, fracture reduction aligns only two bone fragments to their home-position. Meanwhile, for the complex case, fracture reduction needs to align more than two fragments. In some fracture cases, accurate reduction of broken fragments is difficult to achieve due to the desired position of the fragments is not easy to be recognized from available medical images. A 2D standard radiograph or CT images may not be sufficient enough to give a better understanding of complex orthopedic injuries. The virtual preoperative planning attracts surgeon attention to interact with digital medical images platform. It generates 3D model of a fractured bone from a stacked patient's CT images. It also integrates the surgical procedures in a 3D environment to lead advantages of better planning complex fractures. A 3D virtual simulation tool based on a personal computer is employed, enabling surgeons to relocate fracture fragments onto their original position. This laboratory default software, named PhysiGuide, was employed to deal with the reduction of comminuted fracture fragments. It begins with the display and manipulation of CT images on 2D and 3D viewports to allow the user for viewing the fractured bones, as presented in Figure 1.

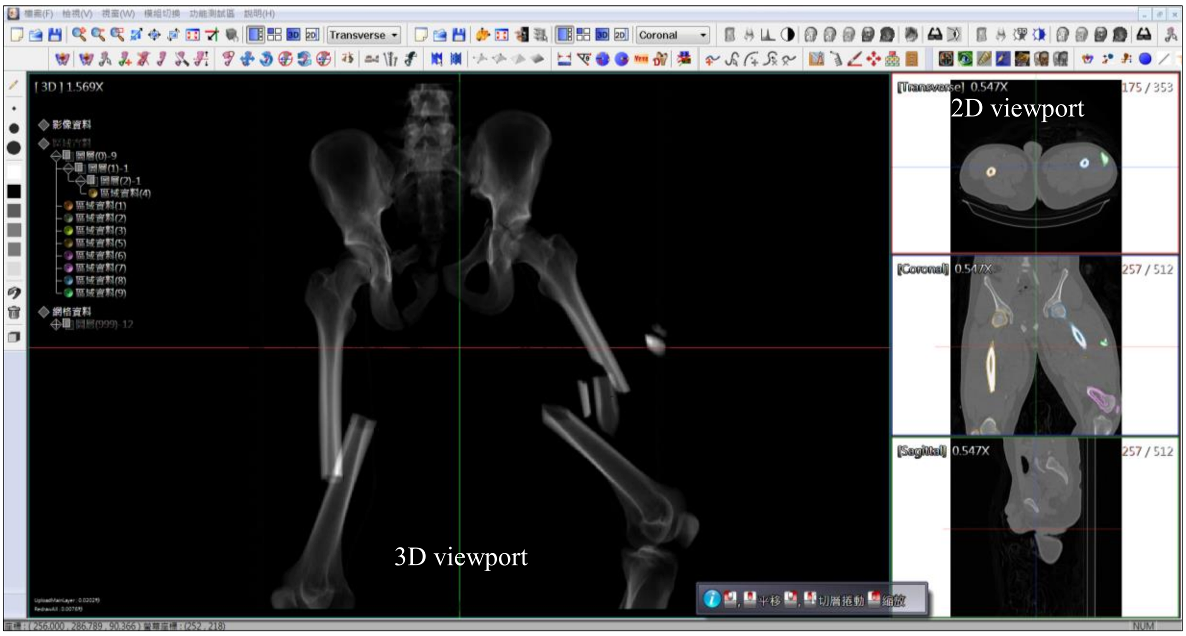


Figure 1. The PhysiGuide software user windows for preoperative planning orthopedic surgery.

Figure 1 presents the comminuted fracture in the hip bone, in left femur, and simple fracture in right femur fragments. In this study, the simple fracture femur is taken as an example due to it frequently encountered injury, the biggest long bone and the one with the most complex post deformity. However, in fact, it is the easiest type of bone to be demonstrated. There are three steps to work into the planning of bone fracture treatment (1) generating anatomical bone and fragments from the scanned 3D images; (2) fixing and stabilizing the fragments to accomplish early recovery and (3) analyzing the virtual fracture reduction under common biomechanical conditions. 3D model of fractured bone is constructed from medical images that represent the bone and fragments involved in a fracture. The 3D models usually represented in a volume data for visualization, in a point cloud for fast interaction and in a triangulation mesh for geometric operation between models purposed. For extracting the meshes from CT stacks, Marching Cubes (MC) algorithm was the most widely used for their simplicity and speed. The size of models generated by these methods depends on the resolution of the medical images and the complexity of the segmented bone structures. Furthermore, the segmentation of medical images is required to obtain the bone regions involved in a fracture. Several studies have been conducted and available on segmentation fractured bone tissue including intensity-based, edge-based, region-based and registration-based. Regardless of the model representing the main purposes of segmentation are to differentiate between bone tissue and other tissues as well as recognition of different bone fragment or labeling [11]. Virtual bone reduction enables to relocate back bone fragments to their original positions and orientations in space. The correspondence between two adjacent bone fragments should be consider to align the complex fracture. In the proposed system, both user interactive and semi-automatic bone reduction method were employed in fragments registration. For user interactive or called also manual bone reduction, each of the bone segments is moved piece by piece through a user interface within three rotations and two translations along the viewing plane [12]. The final result of manual bone reduction must be judged visually. The operating time might lengthen when an excessive number of fragments relocated. In semi-automatic bone reduction, two algorithms are proposed, namely multi-point positioning and mirror positioning. The accuracy of the alignment depends mainly on the accuracy of the point pairs. A registration algorithm [13] is used to align each of the broken fragments with respect to the reference fragment. When all broken fragments are transformed, their might repositioned to original positions in space. For more detailed, a middle shaft fracture femur reduction procedures was presented consists of generating a 3D model from CT-scanned, segmenting and labeling fragments and aligning the two bone fragments into the home position, as depicted in Figure 2.

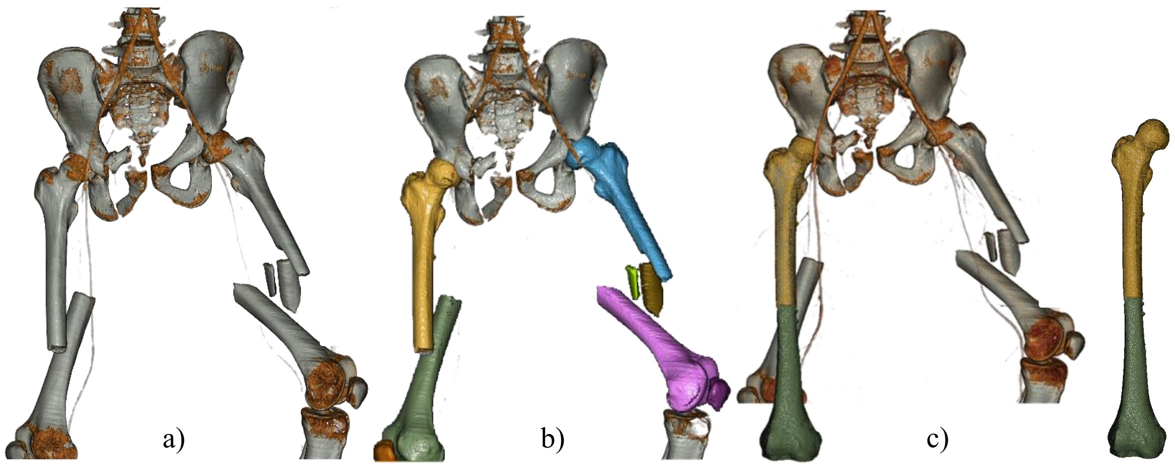


Figure 2. The virtual fracture reduction surgery in the space environment. a) 3D reconstruction from a stacked of CT-images, b) segmentation and labeling the fracture fragments, c) the reduction procedures by paired points registration.

3. Robot-Assisted Fracture Reduction (RAFR)

The robotic manipulator has been widely proposed in orthopedics for assisting fracture fixation, bone lengthening, and deformation correction. The clinician typically drove fractured bone fragments to an anatomically desired position by modifying the rod arms length of the robotic manipulator. This task is accomplished by the clinician with the high requirement in the experience and expertise. As an alternative, the commercial robotic system might hand the same task accompanying with automation mechanism software implementing the mathematical model. The external fixator ring refer to Stewart platform was selected as the main platform. It adopts the analogy of Ilizarov's external fixation device. Stewart platform has several advantageous as a robotic fracture repositioned, in term of high stiffness and precision, repeatability, working space in 6 d.o.f and high load to weight ratio. However, it is not suitable for all application. A 3-RPS (revolute-prismatic-spherical) got a lot of attention, instead of has some ability with Stewart platform, it easy to control and low cost fabrication. According to those reasons, we proposed a novel design of 3 d.o.f star-double triangle spherical parallel manipulator. The basic concept of this manipulator integrating a 3-DOF- Revolute–Prismatic–Sphere and Double Triangular Spherical Planar manipulator into a single device. The main structure comprises a ring base as a fixed platform and equilateral triangular platforms as a moving platform of the robot that fitted into the proximal and distal fragments of the fractured bone using pins or wires. The structure of double-triangle look-like the star composed two combinations of RPS manipulator introduced by K.M. Lee [14] and Triangular Planar-Parallel Robot (PRP) suggested by Daniali [15]. The concept design of this novelty robot shown in Figure 3. This novel manipulator is developed based on three identical RPS manipulator legs. The mechanism consists of the first joint (R-joint) connecting to the base and the last joint (S-joint) attached to the moving platform. The upper side of links are connected to the moving platform by the spherical joint and the other ends of the links are connected to the base platform through the revolute joints. The planar robot is a specific symmetrical closed-loop mechanism, consist of a pair of triangles with straight edges, placed on the top of the frame and another on top of the first triangle sliding along the edge pairs of interconnected points of three fixed edges. The moving platform connected to the base platform by three extensible linear actuators. The lengths of actuators are changed with prismatic joints (P-joints), the platform move on 2 d.o.f rotation and 1 d.o.f in translation. The planar parallel mechanism move in the planar motions.

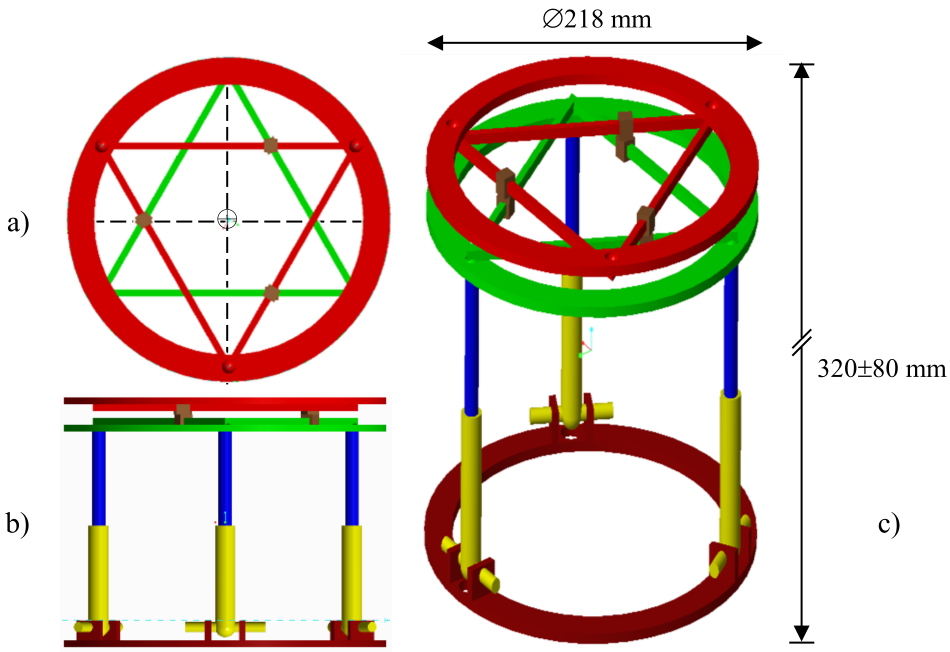


Figure 3. Conceptual design of CAD model RPS manipulator. a) top-view, b) front-view, c) iso-view

The virtual proposed manipulator able to work in the maximum length 320±80 mm and the diameter of the platform is 218 mm. It also can maneuver in XYZ rotation about ± 15-20° and XY translation ± 50 mm, Z translation movement ±237 ÷ 384 mm. Detailed of the parts dimension and platform configuration of the manipulator is presented in table 1.

Table 1. The virtual proposed manipulator platform configuration parameters.

Parts	Dimensions (mm)		d.o.f	Joint range
Top plate (moving platform)	∅218 x 10		-	-
Base plate (fixing platform)	∅218 x 10		-	-
Linear actuator	∅20 x 320±80		1	80 mm
Ball Joints	∅20		3	± 15°
Revolute Joints	∅5		1	± 45°
Movements	Platform Configuration			
Rotation X- α	± 15°			
Rotation Y- β	± 15°			
Rotation Z- γ	± 20°			
Translation X	± 50 mm			
Translation Y	± 50 mm			
Translation Z	± 237 ÷ 384 mm			

Figure 4a depicts the basic concept and architecture of a hybrid 3-DOF-RPS manipulator used to perform virtual reduction simulation of the deformed and fractured bone. Kinematic structure, the coordinate axes are fixed for different joints of manipulator. The frame O_{xyz} fix on to platform base, whereas O triangle centroid of $A_1A_2A_3$ with Z axis perpendicular to platform base. Frame coordinate of $O'_{x'y'z'}$ and $O''_{x''y''z''}$ laying down on the moving platform $B_1B_2B_3$ and $C_1C_2C_3$ with Z axis pointed upward and normal to platform base as shown in Figure 4b. The spatial 3-RPS parallel manipulator comprises of three spherical joints (S) located at the vertices of the equilateral triangle B_i (i = 1, 2, 3) of the moving platform B. Three revolute joints (R) at the corners of the equilateral triangle A_i (i = 1, 2, 3) of the base platform A. Both of fixed base and moved platform merged by prismatic joints. The planar robot is a unique symmetrical closed-loop mechanism with a pair of straight edges triangle. The upper mechanism (platform C) lay down on top of platform B and sliding along the edge pair intersection points of platform.

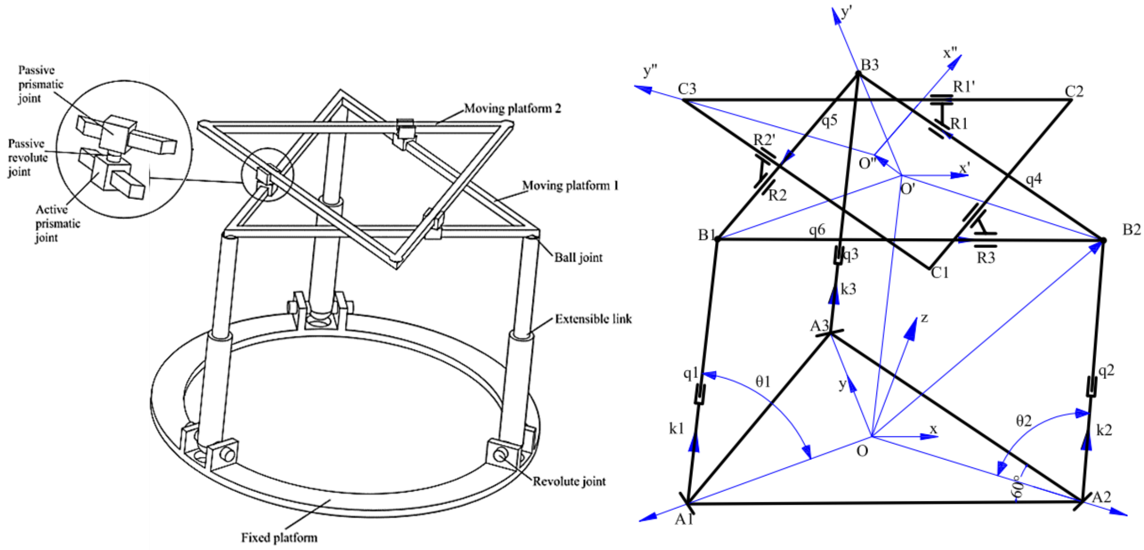


Figure 4. The schematic of RPS manipulator. a) Manipulator joints, b) Kinematic structure

IOP Conf. Series: Materials Science and Engineering **308** (2018) 012010 doi:10.1088/1757-899X/308/1/012010

Assuming the end-effector of the manipulator coincides with the center point O'$_{x'y'z'}$ and O''$_{x''y''z''}$ of the moving upper platform. Base coordinate system of x, y, z, laying on the center point O of the base platform with the plane xy coinciding with the base platform. The joint coordinates are the lengths q_1, q_2 and q_3 of the platform legs. The x'y'z' and x''y''z'' are the coordinate system attached to the moving platform with origin at point O' and O''. Considering the coordinates of the vertices B_1, B_2, B_3 of the upper platform of the manipulator. From the constraints applied by the rotational joints at points 1, 2, 3, the coordinates of the bottom platform points are obtained as follows:

The coordinates of the revolute joints relative to the original of the fixed platform:

$$\overrightarrow{OA_1} = \begin{bmatrix} -\frac{\sqrt{3}}{2}r \\ -\frac{1}{2}r \\ 0 \end{bmatrix} \overrightarrow{OA_2} = \begin{bmatrix} \frac{\sqrt{3}}{2}r \\ -\frac{1}{2}r \\ 0 \end{bmatrix} \overrightarrow{OA_3} = \begin{bmatrix} 0 \\ r \\ 0 \end{bmatrix}$$

The coordinates of the sphere joints in the moving platform O'x'y'z' frame:

$$\overrightarrow{O'B_1} = \begin{bmatrix} -\frac{\sqrt{3}}{2}r \\ -\frac{1}{2}r \\ 0 \end{bmatrix} \overrightarrow{O'B_2} = \begin{bmatrix} \frac{\sqrt{3}}{2}r \\ -\frac{1}{2}r \\ 0 \end{bmatrix} \overrightarrow{O'B_3} = \begin{bmatrix} 0 \\ r \\ 0 \end{bmatrix}$$

and the coordinates of C_1, C_2, and C_3 in frame O"x"y"z":

$$\overrightarrow{O''C_1} = \begin{bmatrix} -\frac{\sqrt{3}}{2}r \\ -\frac{1}{2}r \\ 0 \end{bmatrix} \overrightarrow{O''C_2} = \begin{bmatrix} \frac{\sqrt{3}}{2}r \\ -\frac{1}{2}r \\ 0 \end{bmatrix} \overrightarrow{O''C_3} = \begin{bmatrix} 0 \\ r \\ 0 \end{bmatrix}$$

The length of the individual links are denoted by q_i. In the fixed frame O-xyz, the position the spherical joints B_i can be expressed as:

$$\overrightarrow{OB_i} = \overrightarrow{OA_i} + \overrightarrow{A_iB_i} = \overrightarrow{OA_i} + q_i \cdot \overrightarrow{k_i} \tag{1}$$

and

$$\overrightarrow{OB_i} = \overrightarrow{OO'} + \mathbf{R}.\overrightarrow{O'B_i} = \overrightarrow{OO'} + \{0\} \cdot \overrightarrow{O'B_i} \tag{2}$$

where

$\overrightarrow{OO'} = \begin{bmatrix} x_{0'} \\ y_{0'} \\ z_{0'} \end{bmatrix}$ denotes the position of the origin of the center moving platform 1 in the fixed frame.

R is the orientation matrix of frame O'x'y'z' with respect to Oxyz with α, β, and γ being the RPY angles in the fixed frame

$$R = \begin{bmatrix} \cos(\alpha)\cos(\beta) & \cos(\alpha)\sin(\beta)\sin(\gamma) - \sin(\alpha)\cos(\beta) & \cos(\alpha)\sin(\beta)\cos(\gamma) + \sin(\alpha)\sin(\gamma) \\ \sin(\alpha)\cos(\beta) & \sin(\alpha)\sin(\beta)\sin(\gamma) + \cos(\alpha)\cos(\gamma) & \sin(\alpha)\sin(\beta)\cos(\gamma) - \cos(\alpha)\sin(\gamma) \\ -\sin(\beta) & \cos(\beta)\sin(\gamma) & \cos(\beta)\cos(\gamma) \end{bmatrix} \tag{3}$$

Herewith, there are 6 coordinates but three of them x0', y0', α dependent. Whereas β, γ, and z0' are three generalized coordinates. Similar approaches were used to define the coordinates of the moving platform 2. The velocity analysis and Jacobian matrices were calculate according to equation (1) and (2)

$$q_i \cdot \overrightarrow{k_i} = \overrightarrow{O'B_i} - \overrightarrow{OA_i} \tag{4}$$

where $\overrightarrow{k_i}$ is unit vector along three legs q_i.By substituting the equations (1) and (2) and differentiating equation (4), we found:

$$\dot{q}_\imath \cdot \overrightarrow{k_\imath} + q_i \cdot \left[\dot{\theta}_\imath \times \overrightarrow{k_\imath}\right] = \dot{\overline{OO'}} + \vec{\omega} \times \{0\} \cdot \overrightarrow{O'B_\imath} \tag{5}$$

where θ_i is the angular velocity of leg q_i and ω is the angular velocity of the moving platform 1 respectively to the fixed platform.

$$\dot{q}_\imath = \dot{\overline{OO'}} \cdot \overrightarrow{k_\imath} + \vec{\omega}\left(\overrightarrow{O'B_\imath} \times \overrightarrow{k_\imath}\right) \tag{6}$$

Set the Jacobian matrix

$$J_x = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{7}$$

$$J_y = \begin{bmatrix} \overrightarrow{k_1}^T & \overrightarrow{O'B_1} \times \overrightarrow{k_1} \\ \overrightarrow{k_2}^T & \overrightarrow{O'B_2} \times \overrightarrow{k_2} \\ \overrightarrow{k_3}^T & \overrightarrow{O'B_3} \times \overrightarrow{k_3} \end{bmatrix} \tag{8}$$

hence, arranged the equation (6) become:

$$J_x \cdot \begin{bmatrix} q_1 \\ q_2 \\ q_3 \end{bmatrix} = J_y \cdot \begin{bmatrix} \dot{x}_{0'} \\ \dot{y}_{0'} \\ \dot{z}_{0'} \\ \dot{\alpha} \\ \dot{\beta} \\ \dot{\gamma} \end{bmatrix} \tag{9}$$

4. Methods

The process of investigation synergetic of the combination 3D imaging fragments reduction technique and path planning a parallel robotic mechanism consist of three main consecutive steps reduction-fixation procedure is depicted in Figure 5.

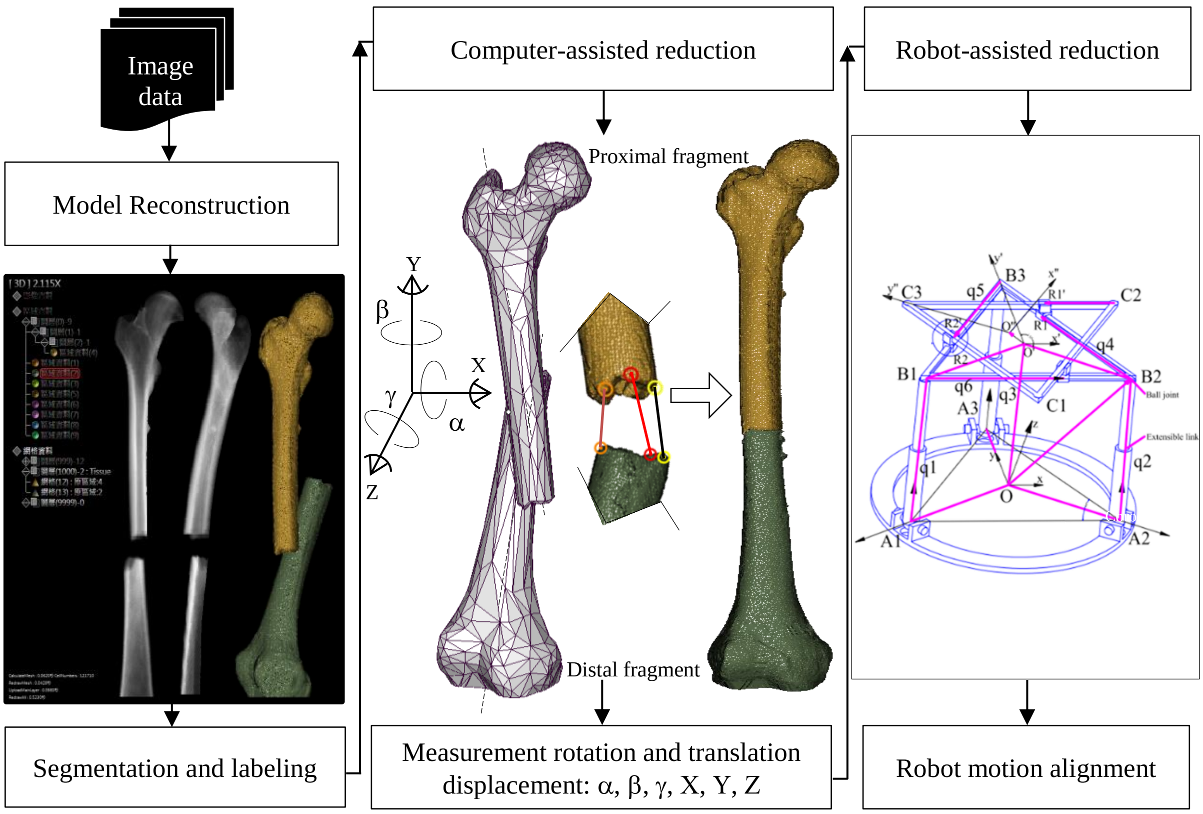


Figure 5. The main procedures of computer-aided preoperative with the planar parallel manipulator

These steps can be described as the following: (1) 3D model of the fractured bone are reconstructed from x-ray or CT-scan radiography. The fracture fragments segmentation and labeling are applied to the specifically desired fracture bone. Then, triangulation mesh is generated for ease manipulation reposition. The fracture fragment displacement in rotation and translation are measuring. (2) The virtual reduction is conducting with a paired point to point registration. The virtual fractured reduction simulation was reconstructed using the software PhysiGuide, version 2.7.2 (NCU Taiwan, bio-images, and clinical assistant laboratory) on a Desktop computer (Intel (R) Core (TM) i5-4440 CPU, 3.1 GHz processor, 4 GB RAM, Windows 7 operating system. All of the parameter measuring such as α, β, γ, X, Y, Z during the virtual reduction is recorded and used as the input for the next step. (3) The relative position of the fragments is determined according to virtual reduction data. Using inverse kinematic solution, an initial robot configuration (the length of the prismatic actuators) is determined to be fixed to the fragments, pull them apart and align them, with the final robot configuration of parallel moving and fixed platforms. The proximal and distal fragments are fixed to the fixed and moving platforms, respectively, by means of pins or wires. The prismatic pairs are actuated until the final configuration is obtained and then locked. The actuators are removed from the robot and the remaining frame acts as an external fixation device until the fracture heals. These steps were designed to be performed automatically under the supervision of the orthopedic surgeon who is able to slow down and/or stop the process. To encourage the fractured bone reduction assisted by robot mechanism, we proposed to develop the graphical user interface (GUI) for the clinician in a user-friendly environment. The clinician performs some measurements on these measured parameters along with certain known variables such as angular parameters, axial rotation, ring radius, legs length to the GUI. The parameters currently outcomes from the result of the virtual fractured bone reduction computer-assisted simulation. Those data will input to GUI for manipulating the reduction deformed bone robot movements. The GUI developed with Unity 5.4 that involves 6 main input box which is Δγ, Δβ, Δz OB, Δx, Δy, as depicted in Figure 6. The coding program is accomplished by the NCU Taiwan, medical assistance robotic system laboratory, with C# programing language refer to coordinate transformation as described in equation 1 to 9 in a windows environment. The simulation is running on a personal computer (Microsoft Windows 7 operating system with Intel Core i5, 3.6 GHz, and 8 GB RAM).

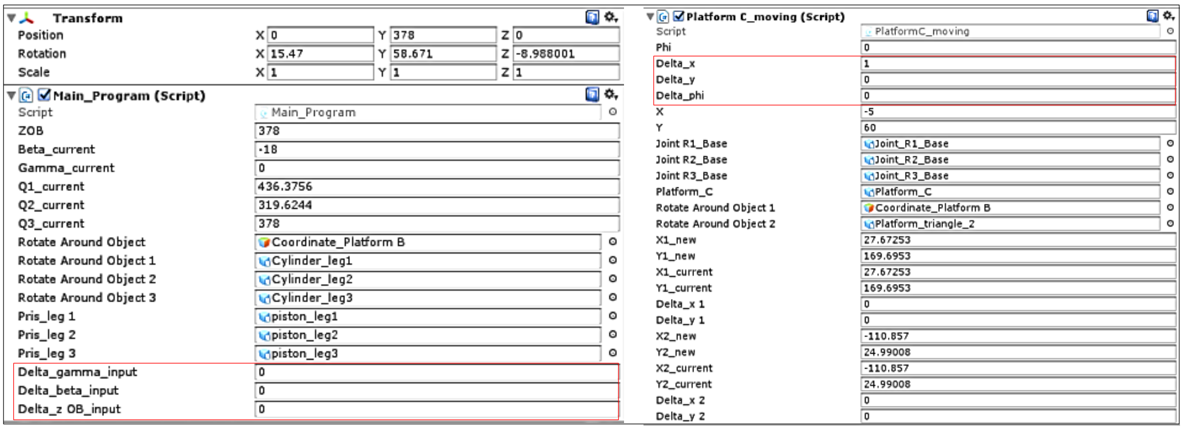
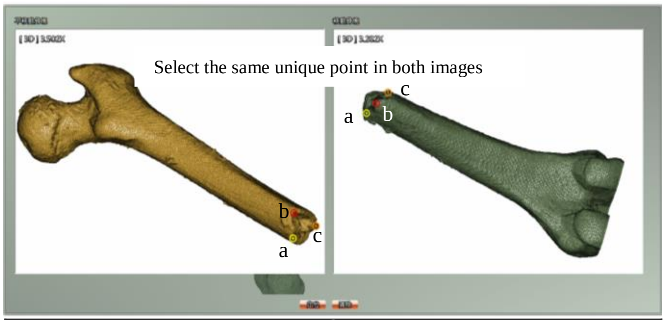


Figure 6. GUI windows displaying the operator interface of robot movement software program

5. Results and Discussion

To evaluate feasibility study of virtual fractured bone reduction and 3-RPS manipulator, we measure displacement of bone fragments and simulate bone reduction using paired point registration. Figure 7 show the measurement result of fractured bone displacement. Then, α, β, γ, ΔX, ΔY, ΔZ values were input into robotic model graphical user interface to control manipulation of arm length, drove fractured fragments back to their original position. The measurement of displaced fragments in translation and rotation were computed. The root mean square deviation was used to evaluate fragments alignment error.



Three translation degree of freedom (d.o.f)	Three rotational degree of freedom (d.o.f)
ΔX = 24.67 ≈ 25 mm	α = 22.30°
ΔY = 27.13 ≈ 27 mm	β = 13.45°
ΔZ = 70.82 ≈ 71 mm	γ = 0°

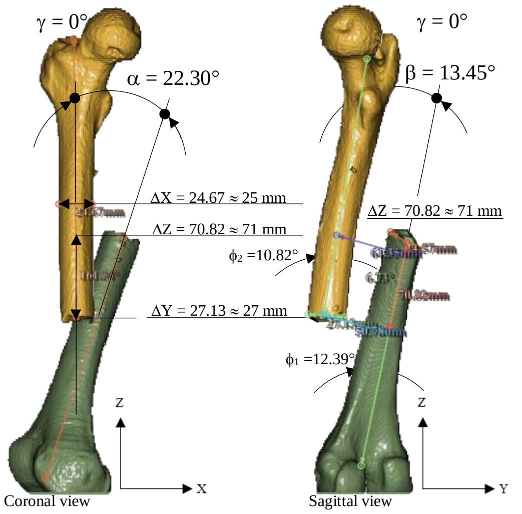
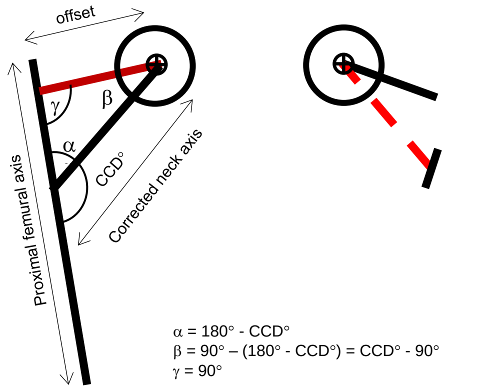


Figure 7. The measurement result of fractured fragments dislocation

The relative length between two centroid bounding box coordinates is measured. The grey colour fragment is fixed as reference, and the brown fragment move to match the reference as shown in Figure 8. Both fragments are realign closest possibly as their anatomy shape respectively to ground truth.

Parameter	Results	
	Fragment 1 (reference)	Fragment 2
$d_s - x$ (m)	0	0.03203
$d_t - y$ (m)	0	0.03411
$d_l - z$ (m)	0	0.02820
α (°)	0	55.17°
β (°)	0	34.3°
γ (°)	0	90°



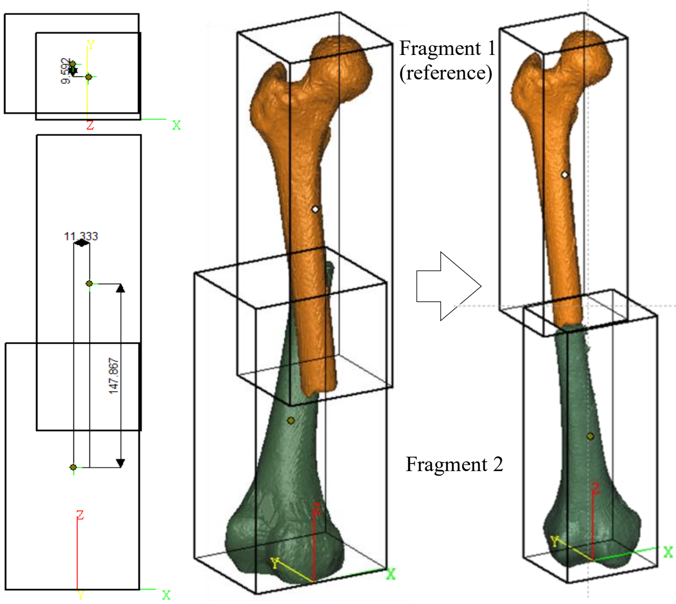


Figure 8. The displacement distance of fractured fragments reduction

The external fixator simulation was conducted to relocate back bone fragments. Actuators lengths, rotation angle of universal and spherical joints were calculated respectively from virtual bone fracture reduction planning. The coordinate transformation of the reduction movement was performed between two adjacent fragments. Using the same setting-up of fragment transformation was applied to execute the manipulator. The moving fragment was drove into the fixed platform to align the bone fragment. In first step, moveable platform was manipulated in such a way trajectory to attain coincidence axis of both fragments, as shown in Figure 9a-e. Then, fragments displacement and miss-orientation from other view was evaluated, as depicted in Figure 9f-j. Finally, the fractured fragments are validated refer to the healthy bone geometry and femoral mechanical axis. Figure 9j-k show 3D pose orientation view.

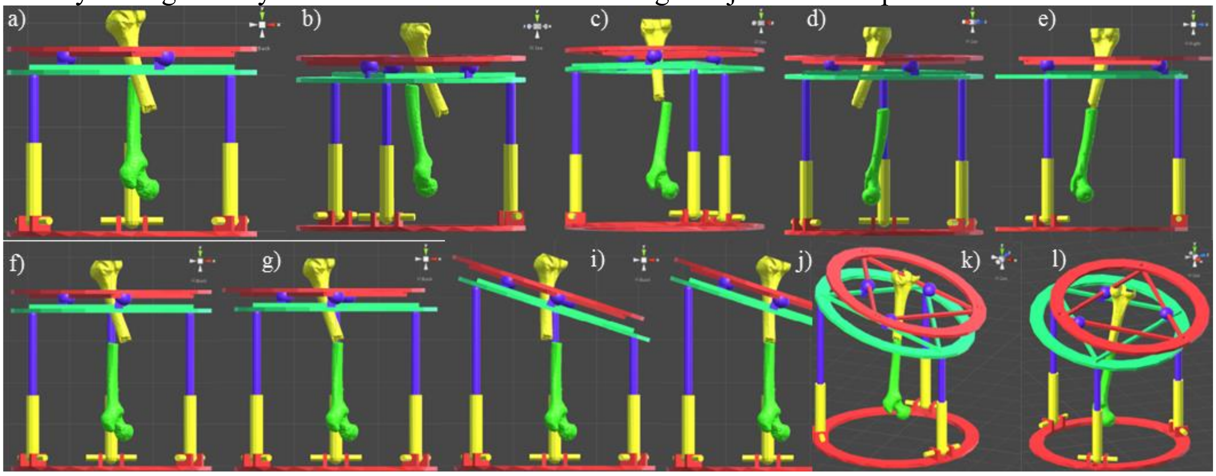


Figure 9. The graphical stages of fracture reduction with sequential adjustment and deformation correctness evaluation. a-e) reduction in anterior view, f-j) posterior view, k-l) iso view

6. Conclusion

In this study, we have developed the virtual model of fractured bone reduction graphical user interface to integrate with 3-RPS manipulator for repositioning the fracture bone into anatomically original position. The proposed integrated system was shown potentially improving alignment visibility of bone reduction. The outcomes simulation of virtual bone reduction were employed to control and manipulate external mechanism actuator to match bone fragments. Due to limitation in accuracy and unpredicted soft tissue, the intuitive supervision is suggested with high skill and experience human operator.

References

[1] Irwansyah, Lai J Y, Lee P Y and Chung C Y 2016 *Proc. of XIV Int. Symp. on 3D Analysis of Human Movement* July 18-21 Taipei Taiwan pp 141-144

[2] Lee P. Y, Lai J. Y, Hu Y. S, Huang C. Y, Tsai Y. C and Ueng W. D 2012 *Biomedical Engineering: Applications, Basis, and Communications* 24 3 pp. 1250007-1 - 1250007-18

[3] Tockus L, Joskowicz, Simkin A and Milgrom C 1998 *Int. Conf. on Medical Image Computing and Computer-Assisted Intervention-MICCAI* pp 29-38

[4] Avsar E and Un K 2016 *Informatics in Medicine Unlocked* 2 pp. 78-91

[5] Mukhherjee S, Rendsburg M and Xu W.L, 2005 *1st Int. Conf. on Sensing Technology*, November 21-23, Palmerstone North, New Zealand pp 78-84

[6] Graham A E, Xie S Q, Aw K C, Xu W L, and Mukherjee S Robotic Long Bone Fracture Reduction Medical Robotics Book edited by Vanja Bozovic ISBN 978-3-902613-18-9 pp.526 I-Tech Education and Publishing Vienna Austria

[7] Westphal R, Winkelbach S, Gosling T, Oswald M, Hufner T, Krettek C, Wahl F. M 2009 *Advances in Robotics Research* Springer Berlin, Heidelberg pp 251-262

[8] Du H, Hu L, Wang T, Zhao L, Li Y, Liu DZhang L, He C, Zhang L, Hou H, Zhang L, Tang P 2015 *The Int. J.l of Medical Robotics and Computer Assisted Surgery* 11 pp. 348-359

[9] Majidifakhr K, Kazemirad S and Farahmand F 2009 *Studies in Health Tech. and Inf.* pp 142-177

[10] Avsar E, Akcali I. D, Aydin A, Un M. K, Mutlu H, Ibrikci T, Ozkan C, Bicer O. S, 2015 *Cukurova Universiti Muhendislik Mimarlik Fakultesi Dergisi* 20 (2) pp 93-101

[11] Jimenez-Delgado J. J, Paulano-Godino F, Pulido Ram-Ramirez R, Jimenez-Perez J. R 2016 *Medical Images Analysis* 30 pp 30-45

[12] Lee P. Y, Lai J. Y, Yu S. H, Huang C. Y, Hu Y. S and Feng C. L 2013 *JMBE* 34 4 pp 368-376.

[13] Lai J. Y, Chen K. J 2007 *The Int. J. of Advanced Manufacturing Technology* 32 11 pp 1188–1200

IOP Conf. Series: Materials Science and Engineering **308** (2018) 012010 doi:10.1088/1757-899X/308/1/012010

[14] Lee K. M and Arjunan S. A 1991 *IEEE Transactions on Robotics and Automation*, 7 5 pp 634-641
[15] Daniali M, Zsombor-Murray H. P, Angeles P. J, 1993 *Computational Kinematics*, pp 153-164