



Experimental Evaluation of a 3-Armed 6-DOF Parallel Robot for Femur Fracture Surgery

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This paper presents the experimental position and force testing of a 3-armed 6-DOF Parallel Robot, Robossis, that is specifically designed for the application of long-bone femur fracture surgery. Current surgical techniques require a significant amount of time and effort to restore the fractured femur fragments' length, alignment and rotation. To address these issues, the Robossis system will facilitate the femur fracture surgical procedure and oppose the large traction forces/torques of the muscle groups surrounding the femur. As such, Robossis would subsequently improve patient outcomes by eliminating intraoperative injuries, reducing radiation exposure from X-rays during surgery and decreasing the likelihood of follow-up operations. Specifically, in this paper, we study the accuracy of the Robossis system while moving in the operational workspace under free and simulated traction loads of (~ 50 – 1100 N). Experimental testing in this study demonstrates that Robossis can reach the most extreme points in the workspace, as defined by the theoretical workspace, while maintaining minimal deviation from those points with an average deviation of 0.324 mm. Furthermore, the force testing experiment shows that Robossis can counteract loads that are clinically relevant to restoring the fractured femur fragments' length, alignment and rotation. In addition, we study the accuracy of Robossis motion while coupled with the master controller Sigma 7. The results show that Robossis can follow the desired trajectory in real-time with an average error of less than 1 mm. To conclude, these results further establish the ability of the Robossis system to facilitate the femur fracture surgical procedure and eliminate limitations faced with the current surgical techniques.

Keywords: Robot-assisted surgery; femur fractures; parallel mechanism; Robossis.

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1. Introduction

Surgical robotics has surged into the spotlight of surgical technology in the last 40 years due to the demand for

increased speed and accuracy needed for the evolution of healthcare [1–4]. The rise in fractures since the early 2000s [5,6] has led to extensive research and studies conducted on robots specifically designed for fracture alignment surgeries [7,8]. Long-bone fractures have been of particular interest for robot-assisted surgeries due to the limitation of current methods, including the substantial amount of force required to reposition and fixate the fragments, the high rates of malalignment and malrotation, and the elongated X-ray exposure to the operating staff [7–10].

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Although robot-assisted surgeries have been studied for years, there has not been a properly designed system that can handle the complex extremities of long-bone fracture fixation, including the need for immense forces/torques competence (517 N and 74 N·m, respectively), pinpoint accuracy and the large operational robot translation and rotational workspace (Table 1). To address these extremities faced during long-bone fracture surgeries, our group has presented a novel design of a 3-armed 6-DOF parallel robot, Robossis, theoretical analysis [11–15], preliminary experimental force and position testing [16] and cadaveric experiment [17].

Furthermore, in this study, we present more extensive experimental force and position testing for the Robossis system. Specifically, we study the accuracy of the Robossis system while moving in the operational workspace with free and varying loads applied to the structure. We model the forces as springs with loads increasing to 1100 N. In addition, we study the accuracy of Robossis motion coupled with the master controller (Sigma-7, Force Dimension – Switzerland).

This paper is organized as follows. Section 2 presents the clinical challenges and requirements for femur fracture surgery. Section 3 presents the Robossis system architecture. Section 4 presents the experimental testing, including workspace, movement in a straight line, load insertion, and real-time motion via the master controller. Finally, Sec. 5 presents the discussion, and Sec. 6 concludes.

2. Clinical Challenges and Requirements

A surgical robot developed for the application of long-bone femur fracture surgery must be designed to meet

the clinical requirement. The required accuracy for the alignment of the long-bone femur fracture is defined based on the Thoresen scoring system [44], ± 1 cm and $\pm 5^\circ$ for translational and rotational alignment, respectively. Malrotation is one of the most significant complications of femur fracture surgery (Table 2). Table 2 shows that the outcome of current surgical techniques to treat long-bone femur fractures results in a high rate of malrotation, which alters the patient's gait mechanics and efficiency [45,46].

Furthermore, the long-bone femur is surrounded by the largest muscle groups in the human body, which require large traction forces/torques during the surgical operation. As such, manipulation of the fractured femur fragments is very difficult and requires the extensive clinical expertise of multiple doctors. Previous studies [52,53] have defined the traction forces/torques requirements during femur fracture surgery. Based on the anatomical [52,53] medial-lateral axis, the anterior-posterior axis, and the femoral shaft axis, the maximum forces required were defined as 202, 517 and 505 N, respectively. In addition, the maximum torques required in the medial-lateral axis, the anterior-posterior axis, and the femoral shaft axis were defined as 16.4, 38.3 and 74 N·m, respectively.

Additionally, the required rotational and translational workspaces for a robotic system designed for long-bone femur fracture surgery can be deducted based on the previously reported literature on post-operative malrotation and shorting of the leg [51,54,55]. We provide a quantitative approximation for the desired workspace limits in the femoral shaft axis in Table 3. This approximation is based on the maximal shortening and malrotation along the femoral shaft axis observed in

Table 1. Robot-assisted systems for femur fractures. Gough–Stewart platform (GSP), Serial (S), Parallel (P), Hybrid (H) and Not Reported (NR).

Year of research	Mechanism type	Subject study	Max load force (N)
1995 [18]	S	Bone model	50
2004 [19]	S, Stäubli RX130	Bone model	240
2004 [20]	P, GSP	Human model	NR
2006 [21]	S, Stäubli RX90	Human cadaver	< 300
2008 [22]	S, Stäubli RX90	Rat model	250
2009 [23]	S, Stäubli RX90	Bone model	< 300
2010 [24]	S, Stäubli RX90	Human cadaver	< 300
2012 [25–27]	S-P-H	Position testing	600
2013 [28,29]	P, GSP	Bovine femoral	NR
2013 [30]	P, GSP	Human cadaver	NR
2014 [31]	P, GSP	Bone model	2460
2017 [32–35]	P, GSP	Bovine bone	1243
2016 [36–39]	S-P-H	Human cadaver	< 300
2020 [40]	P, GSP	Bone model	NR
2022 [41]	P, GSP	Bone model	500
2022 [42]	P, GSP	Animal model	561
2022 [43]	Serial + Traction Table	Bone model	158

Table 2. Malrotation of the proximal (P), shaft (S) and distal (D) femur occurs at a high rate after surgical operation.

Study type	Study sample size	Malrotation rate	Malrotation definition
S [9]	530	28%	$\geq 10^\circ$
P [47]	70	24%	$\geq 10^\circ$
S [48]	76	28%	$\geq 15^\circ$
D [49]	51	27%	$\geq 12^\circ$
S [50]	24	41%	$\geq 10^\circ$
S [51]	24	41%	$\geq 15^\circ$

Table 3. Major clinical requirements for a designed robot-assisted surgery system for the application of long-bone femur fracture.

Parameter	Clinical requirement
Accuracy [44]	$\pm 1 \text{ cm}, \pm 5^\circ$
Loads [52,53]	517 N, 74 N*m
Trans and Rot Workspace (femoral shaft axis) [51,54,55]	$\pm 5.4 \text{ cm}$ $\pm 40^\circ$

the literature. As such, a designed system for femur surgery must meet the desired accuracy, load insertion and workspace requirements to manipulate the long-bone femur fracture.

3. Robossis System Architecture

Robossis system is designed based on a 3-armed parallel mechanism where each arm is placed on a moving and fixed ring (Fig. 1). The Robossis system is designed to meet the clinical requirements of femur fracture surgery which includes (1) adequately applying the large traction forces/torques, (2) precisely aligning the fractured bone and (3) manipulating the distal bone fragment during the surgical procedure. Each arm of the Robossis includes three joints: Universal, prismatic and spherical (Fig. 1). The universal joint connects the rotary actuator shaft to the lower arm and is fixed on a semicircle to the fixed platform. In addition, the spherical joints connect the upper parts of the linear actuators to the moving ring.

To satisfy the needs of the necessary load insertion during femur fracture surgery, Robossis actuators are selected. A 260 W Autronics-A8K stepper motor with a nominal torque of 0.83 Nm powers the rotary actuator. The Autronics-A8K is also coupled with an Apex 60:1 gearbox, raising the maximum holding torque to 48.6 Nm for a total of 145.8 Nm. A revolute joint formed from a needle bearing joins the gearbox shaft to the lower part of the arm. Each arm includes a linear actuator of a Hiwin KK40 linear guide with a 1.0 mm pitch. Each linear actuator is powered via an 80 W Autronics-A3K stepper motor with a nominal torque of 0.24 Nm, resulting in a maximum insertable linear force of 1527 N at each arm.

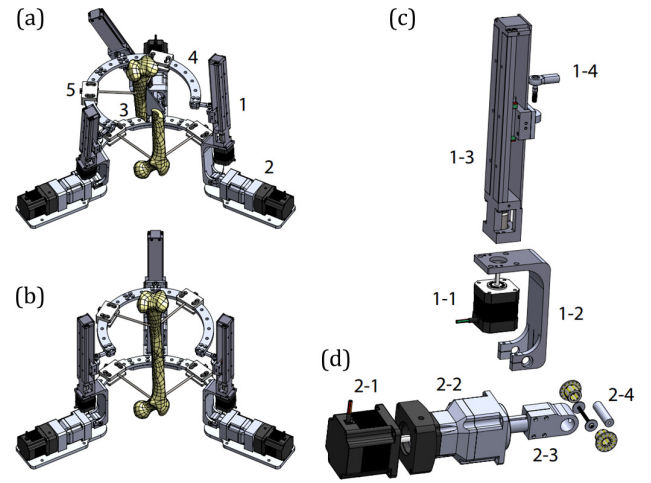


Fig. 1. (a) Robossis mechanism [17] consists of three arms (1-2) where each arm is attached to (3) a fixed ring, and (4) a moving ring. The bone is attached to the patient using surgical rods (5). (b) The Robossis mechanism after manipulation of the fractured bone to demonstrate the various joints movement on bone manipulation. Each arm of Robossis (c-d) is equipped with an Autronics-A3K stepper motor (1-1), (1-2) Hiwin KK40 linear guide (1-3) and spherical joint (1-4), Autronics-A8K actuator (2-1), Apex 60:1 gearbox (2-2), universal joint (2-3) and roller bearing and thrust roller bearing (2-4).

Therefore, using the A3K micro-stepper in the proposed system, Robossis can theoretically insert up to 4559 N.

3.1. Inverse kinematics analysis

The inverse kinematics of the Robossis system was developed to maneuver the endpoint effector (Fig. 2) [11–14].

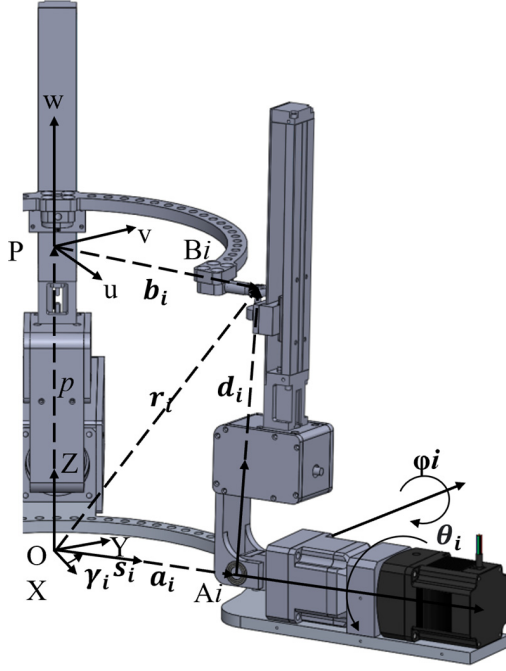


Fig. 2. Kinematic variables of the i th arm are shown. θ_i is the active rotation, followed by the passive ψ_i rotation.

Given the desired position and orientation of the end-point effector (P), the required length of the linear actuator (d_i) and the rotation of the active joint (θ_i) are computed. Referring to Fig. 2, a_i and b_i represents OA_i and PB_i , respectively. Denoting r_i and p as a position vector $[x \ y \ z]^T$ in frame {A}, it can be concluded from the structure that

$$r_i - a_i = p + b_i - a_i, \quad (1)$$

where the left-hand side is the length vector of the linear actuator (d_i), simplifying and using Euclidean norm, d_i can be expressed as

$$d_i = \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2}. \quad (2)$$

Also, the active joint (θ_i) is expressed as shown in the following equation:

$$\theta_i = \sin^{-1} \left(\frac{\sin(\gamma_i) * (x - x_i) - \cos(\gamma_i) * (y - y_i)}{d_i \cos(\psi_i)} \right), \quad (3)$$

where γ_i is the i th location of each arm, and ψ_i is the angle of the passive joint ($i = 1, 2, 3$).

3.2. Trajectory generation

Trajectory generation of the Robossis system can be achieved with a manual or real-time motion via the master controller. For manual control, a time-controlled trajectory generation scheme is implemented using a

trigonometric function:

$$x(t) = \begin{cases} x_0, & t < t_0 \\ x_0 + dx, & t > t_0 + dt \\ \frac{dx}{2} * \sin \left(\frac{180}{dt} * (t - t_0) - 90 \right) + x_0 + \frac{dx}{2}, & \end{cases}, \quad (4)$$

where x_0 is the initial position, dx is the desired change of motion, t_0 is the initial time of change and dt is the desired time to complete the motion. The time-controlled trajectory scheme is generalized to all translational and rotational motions.

Furthermore, real-time motion of Robossis was coupled with the master controller with a trajectory generation scheme using splines and control via waypoints (Fig. 3). A cubic spline $S_{3,n}(t)$ is a piecewise cubic polynomial and mathematically defined by four coefficients, $a_{3,n}$, $b_{3,n}$, $c_{3,n}$ and $d_{3,n}$ as follows:

$$S_{3,n} = \begin{bmatrix} d_{3,0}(t)^3 + c_{3,0}(t)^2 + b_{3,0}(t) + a_{3,0} \in [t_0 \ t_1] \\ d_{3,1}(t)^3 + c_{3,1}(t)^2 + b_{3,1}(t) + a_{3,1} \in [t_1 \ t_2] \\ \vdots \\ d_{3,n}(t)^3 + c_{3,n}(t)^2 + b_{3,n}(t) + a_{3,n} \in [t_{n-1} \ t_n] \end{bmatrix}, \quad (5)$$

where $a_{3,n}$, $b_{3,n}$, $c_{3,n}$ and $d_{3,n}$ are solved using the conventional clamped cubic spline algorithm [56]. Furthermore, the velocity at each piecewise cubic polynomial can be estimated as follows:

$$S_{3,n}(t)' = 3d_{3,n}(t)^2 + 2c_{3,n}(t) + b_{3,n} \in [t_{n-1} \ t_n]. \quad (6)$$

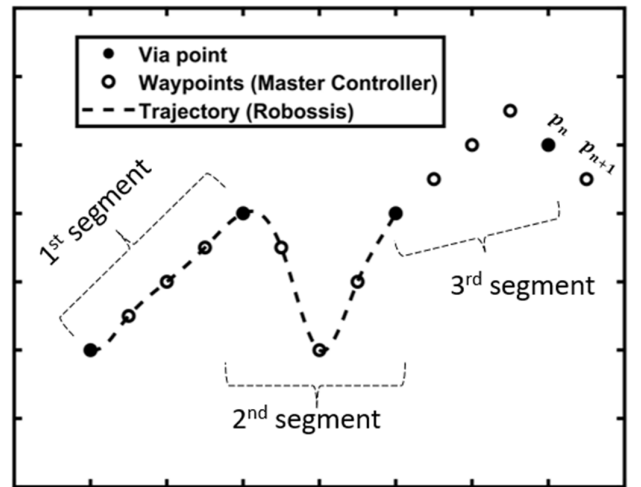


Fig. 3. A trajectory generation scheme implemented to couple the motion of the master controller at real-time. Via points are used to connect the waypoints and the segments of the trajectory.

Using the clamped cubic spline, a third-order continuity for the position, velocity and acceleration is ensured through each segment of the trajectory, and a maximum of four boundary conditions must be specified (i.e. initial and final position and velocities) for each trajectory segment.

We implement via control points to connect the clamped cubic spline's trajectory segments to extend the trajectory to a real-time motion. Constraints are imposed on the via points to obtain a smooth trajectory which includes a velocity constraint. The velocity at the via point is estimated using the central differential method as follows:

$$V_{\text{via}} = \left(\frac{p_{n+1} - p_n}{t_{n+1} - t_n} + \frac{p_n - p_{n-1}}{t_n - t_{n-1}} \right) * \frac{1}{2}. \quad (7)$$

As such, motion coupling of the master controller with Robossis is achieved with the trajectory generation scheme.

4. Experimental Testing

Experimental testing of the Robossis system is conducted to study the accuracy and load insertion capability. The Robossis system is manufactured using computer

numerical control (CNC) (frame material: Al 6061) machining and assembled as shown in Fig. 4(a). The mechanism consists of (1) a fixed ring, (2) a moving ring, (3) linear actuators and (4) rotary actuators. Also, (5) shows that the rings are attached to the fractured bone through half-pin rods. Figure 4(b) presents the compact workstation of the Robossis system, which includes (1) a touch screen control panel and (2) the 7-DOF haptic Sigma-7 master controller. Additionally, Fig. 4(c) shows the control panel of the Robossis system, where the user can switch between the manual and real-time master controller motion. The control panel allows the user to lock the movement of the master controller to any desired direction and adjust the speed of the motion.

Furthermore, the performance of Robossis was determined through multiple experimental testing procedures, including workspace, movement in a straight line, load insertion and real-time motion via the master controller. These preliminary testing procedures were conducted to determine the ability of Robossis to be successful in aligning and restoring the length of the femur fragments in the clinical setting.

Also, we implement the Euclidean distance between the actual (A) and theoretical (Th) values as the error metric for analysis in this study.

$$\text{Error} = \sqrt{|X_A - X_{Th}|^2 + |Y_A - Y_{Th}|^2 + |Z_A - Z_{Th}|^2}. \quad (8)$$

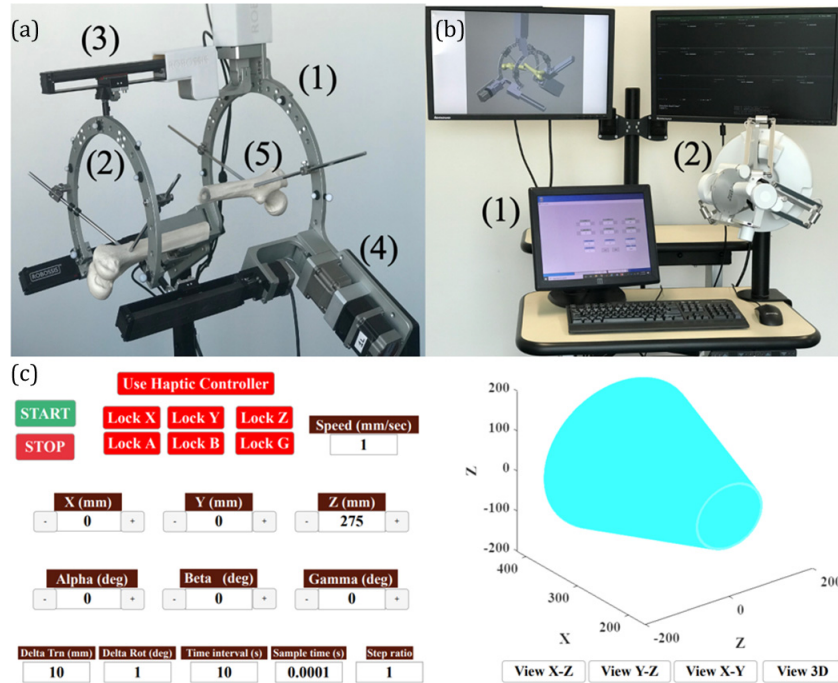


Fig. 4. (a) The fully assembled Robossis system. The mechanism consists of a (1) fixed ring, (2) moving ring, (3) linear actuator and (4) rotary actuator. The rings are attached to the fractured bone through half-pin rods (5). (b) workstation which include (1) touch screen control panel, (2) 7 DOF sigma-7 master controller and screen monitors for real-time feedback on the performance of the robot. (c) the control panel of the Robossis system where the user can switch between the manual and real-time master controller motion.

4.1. Workspace testing

Workspace testing of Robossis is completed to determine the system's accuracy in moving to different locations in the operational workspace. During testing, Robossis was tasked to move to locations in the operational workspace for every 5° and increased height and radius by 10 mm and 3 mm, respectively. The motion of Robossis was coupled with an optical tracking system (Optitrack Flex 13, residual within 0.5 mm, NaturalPoint, Inc. DPA Opti-Track) to determine the accuracy of Robossis in reaching these locations. The results of the workspace testing shown in Fig. 5 illustrate that Robossis can reach the most extreme points in the workspace while maintaining minimal deviation from those points. Furthermore, the box plot shown in Fig. 5 illustrates that the deviation in the workspace testing had an average and maximum Euclidean error of 0.324 and 3.84 (mm), respectively.

4.2. Load insertion

The femur is surrounded by the strongest muscle groups, which require large traction forces/torques during surgical manipulation. As such, to simulate the muscle traction forces and determine Robossis load insertion ability, a preliminary force testing rig was developed with three force gauges (WeiHeng Mini Portable Electronic Scale, capacity = 1471 N) and three springs (Fig. 6). The force testing rig is depicted in Fig. 6 where the springs and force gauges were connected to the proximal and distal half-pins of Robossis moving and fixed rings.

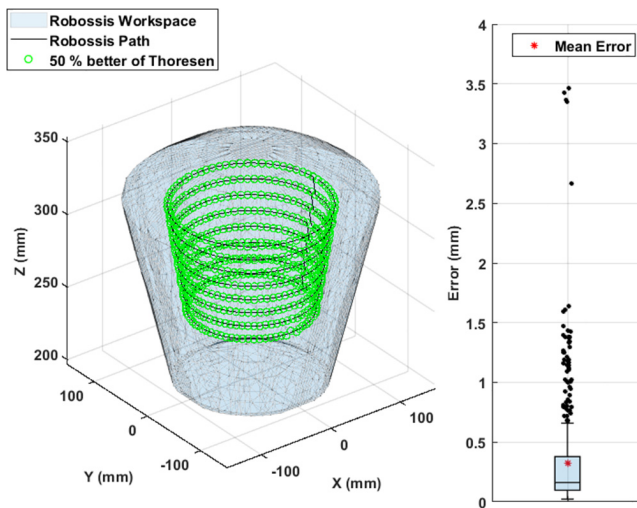


Fig. 5. Experimental testing of the workspace presented as the Euclidean error between the desired and measured locations read by the Optitrack system. The green coloring indicates that each marker exceeded the clinical requirement of at least 50% better than the Thoresen metric. Also, the box plot shows an average and maximum Euclidean error of 0.324 (mm) and 3.84 (mm), respectively.



Fig. 6. The force testing benchtop model includes three force gauges (1) and three springs (2). Also, the force gauges and springs were attached to Robossis moving and fixed rings.

The testing procedure tasked Robossis to move in an increment and extend the springs to their maximum resistive force. During this test procedure, the benchtop model was able to generate a resistive force of ~ 1100 N and Robossis was able to withstand this resistive force, as shown in Fig. 7. As such, Robossis is able to insert two times more than the required traction forces as reported in the literature.

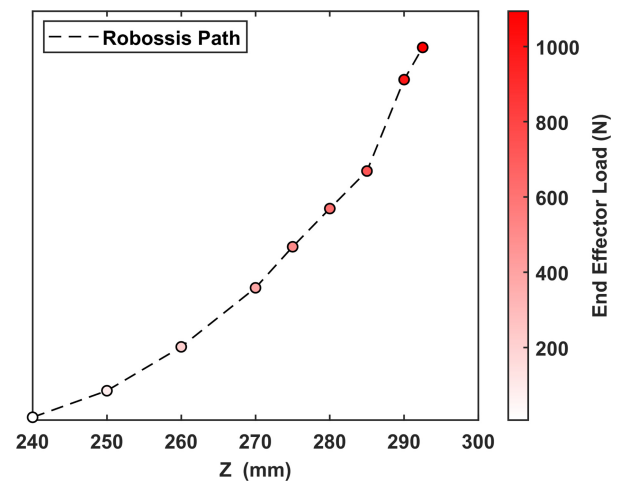


Fig. 7. Robossis was tasked to move in an increment and extend the springs to their maximum resistive force (~ 1100 N). As such, Robossis is able to insert two times more than the required traction forces as reported in the literature.

4.3. Straight line testing

A movement in a straight-line testing procedure was conducted to further investigate the accuracy of Robossis while experiencing external forces. A testing procedure was completed where Robossis was tasked to follow a square path of 160 mm by 160 mm. The optical tracking system measured the location of the endpoint effector along the path to determine the accuracy throughout the testing procedure. Two different testing setups were implemented to introduce varying stresses on the frame of Robossis during movement. (1) No external loads and (2) external loads in the form of springs and force sensors to simulate passive muscle traction forces. The results show that the Robossis mechanism meets the clinical requirement of 50% better than the “excellent” Thoresen metric parameter both without external loads and with loads up to ~ 600 N of force (Fig. 8).

4.4. Motion via master controller

Real-time motion testing of Robossis is completed to determine the system’s accuracy when moving to different locations in the operational workspace. During testing, Robossis was tasked to follow the motion of the

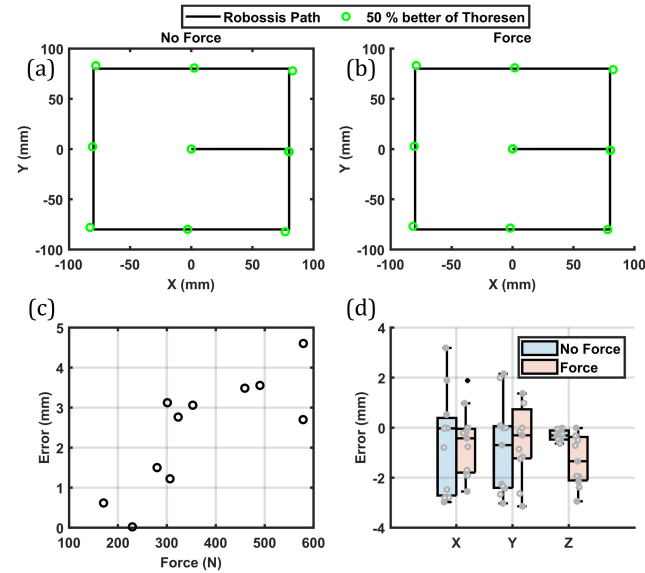


Fig. 8. (a) and (b) Straight line movement testing is presented as the comparison of Robossis while moving with and without external force. The results show that the Robossis mechanism performs 50% better than the Thoresen metric both with and without external load. (c) Euclidean error vs. the inserted force presents a correlation determination (r^2) value of 0.6. (d) The box plot shows a maximum mean absolute error of 1.33 mm in the z -direction while moving with loads. Also, a maximum absolute error of 3.14 mm is observed in the y -direction while moving with loads.

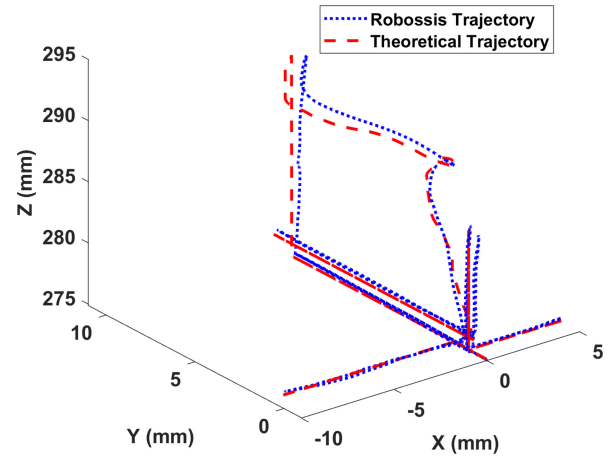


Fig. 9. Robossis is able to follow the motion of the user’s hand at real-time using the trajectory generation scheme. The error analysis shows an average error of less than 1 mm between Robossis system and the user’s hand desired trajectory.

user’s hands at real-time in the operational workspace, and we determined the error of the motion.

The results in Fig. 9 show that Robossis can follow the desired trajectory of the user’s hand in real-time using the trajectory generation scheme implemented using splines. The error analysis shows an average error of less than 1 mm between the Robossis system and the user’s hand desired trajectory. Furthermore, Fig. 10 shows a comparison between the trajectory of the user’s hand (via the master controller), theoretical trajectory and actual trajectory (Robossis) for all X , Y and Z directions. The analysis shows that the absolute error in each

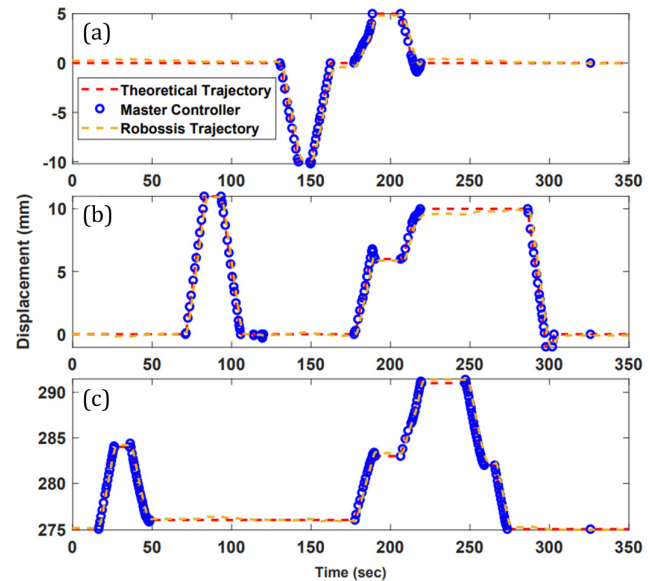


Fig. 10. Comparison between trajectory of the user hand (via the master controller), theoretical trajectory and actual trajectory (Robossis) for all X (A), Y (B) and Z (C) directions.

direction was less than 1 mm, and there was no overshoot observed in the trajectories.

5. Discussion

The experimental position and force testing conducted in this study, and previous studies completed by our group, including the theoretical analysis [11–15], preliminary experimental force and position testing [16] and cadaveric experiment [17] further reinforce the advantages of the Robossis system as compared to the current state-of-the-art surgical techniques and previous attempts of robotic development (Table 1). The Robossis system is designed to meet the clinical requirements of femur fracture surgery which include (1) Sufficient forces and torques to overcome the passive muscle forces, (2) precisely aligning the fractured bone and (3) manipulating the distal bone fragment during the surgical procedure.

As compared to the previous robotic development, the Robossis mechanism has the advantage of meeting the required loads for the long-bone femur fracture (~ 517 N), the required accuracy following the Thoresen metric, and the required operational workspaces in the femur shaft axis ($\pm 50^\circ$ and ± 70 mm). Creating a robot-assisted system using the Gough–Stewart Platform architecture has resulted in limited rotations around the femoral shaft axis. ($\pm 17^\circ$ [28,29]). Also, serial robots have not been shown to generate the required forces/torques (< 300 N). The limitations of traditional serial and parallel mechanisms will prevent the patient from being positioned at the surgeon's discretion, leading to higher risks of patient injury, further surgical complications and malalignment-related complications.

Furthermore, Essomba and Nguyen Phu [40] presented a novel alternation of the Gough–Stewart platform and the design of its components for the application of long-bone fracture surgery. Theoretical analysis of their proposed mechanism presented unique properties where it showed that the mechanism could achieve $\pm 180^\circ$ rotation around the femoral shaft axis. However, their experimental testing was based on preliminary bone testing, and the feasibility of the system in the clinical setting has not been demonstrated yet [40].

In the same vein, the workspace and straight-line testing demonstrate the accuracy of Robossis movement in the operational workspace as desired by the theoretical values. Furthermore, it shows the reliability of the control software and its inverse kinematics model to deliver the proper joint velocities to move Robossis precisely in a six-dimensional space. Additionally, the real-time motion study shows that Robossis is able to follow the motion of the user's hand and maintains a high level of accuracy over numerous movements with an average error of less than 1 mm.

Furthermore, the load insertion tests show that Robossis can deliver the required loads that are clinically relevant to restoring the length, alignment and rotation of the fractured femur fragments. As we were able to deliver traction forces of ~ 1100 N along the femoral shaft axis, this study reinforces the advantage of the Robossis system for femur fracture surgeries. For future studies, it would be prudent to reconsider animal models rather than springs to determine the specific spatial accuracy under large loads. Additionally, it would be prudent to consider a closed-loop control mechanism to account for some of the errors due to joint clearances.

Overall, previous studies completed by our group, including the theoretical analysis [11–15], preliminary experimental force and position testing [16], cadaveric experiment [17] and the current study form the basis for a complete robot-assisted system for the application of femur fracture surgery. In learning the current abilities and limitations of Robossis, we seek to implement the discussed improvements in the robotic design to prepare for additional cadaveric and clinical experiments. Such experiment will be beneficial in uncovering any further limitations for applications of the proposed robot and workflow that have not been discussed in this paper.

6. Conclusion

To successfully restore the length, alignment and rotation of the fractured femur fragments, the femur fragments must be manipulated and returned to their correct anatomical position. All of this must be done while the surgeon is exerting a large traction force (~ 517 N). In this study, we have been able to successfully present the experimental position and force testing for a 6-DOF 3-armed parallel robot that is designed to reduce and manipulate the femur fractured fragments by applying the needed traction forces that counteract the muscle payload surrounding the human femur.

The feasibility of the system was experimentally evaluated through the testing of the workspace, movement in a straight line, load insertion and real-time motion via the master controller. Through experimental testing, Robossis system has the potential to be used clinically in order to improve the quality of fracture reduction and realignment with no need for repetitive manipulations and a high amount of radiation exposure to the operating staff and patients.

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