Torque Reduction of a Reconfigurable Spherical Parallel Mechanism Based on Craniotomy Experimental Data

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Abstract: This paper deals with a robotic manipulator dedicated to craniotomy with a remote center of motion based on a Spherical Parallel Manipulator (SPM) architecture. The SPM is proposed to handle the drilling tool through the requested craniotomy Degrees of Freedom (DoF) with two rotations. The proposed architecture allows one degree of redundancy according to the total DoF. Thus, a first contribution of this work focuses on the experimental analysis of craniotomy surgery tasks. Secondly, its behavior is improved, taking advantage of the redundancy of the SPM using the spinning motion as a reconfiguration variable. The spinning angle modulation allows the reconfigurable manipulator to minimize its motor torques. A series of motion capture and force experimentations is performed for the analysis of the kinematic and force interaction characterizing Burr hole craniotomy procedures. Experimentations were carried out by a neurosurgeon on a human cadaver, ensuring highly realistic conditions.

Keywords: reconfigurable spherical parallel mechanism; craniotomy; motion capture; torque minimization

1. Introduction

1.1. Craniotomy

Several achievements in neurosurgery have been made in the last decade and presented advanced treatment options for patients with severe diseases, epilepsy for instance, including the exclusion of brain tissue. Hence, during the intervention, reaching the patient’s brain is a necessary task for the surgeon, and this can be performed during a craniotomy. Specific surgical instruments have been developed and proposed to neurosurgeons to cut and remove a part of the head’s bone, called the “bone flap” [1]. Several types of drills combined with several types of tips can be used regarding the specific type of craniotomy to be performed [2], and most of them are semi-automatic. This ensures more safety constraints contrary to classic tools [3,4]. However, we can find no automatic drilling tool that is used in some complex interventions and by experienced neurosurgeons. The shape of the tip of this drill is presented as a ball and can also be used for radial and axial drills. This drill is referred to as “diamond burr” or “rosen burr”, depending on the surface geometry of the drill Burr cut. It is clear that through this instrument, the surgeon can take advantage by changing the drilling direction more easily and also perform a free motion with a high level of dexterity. Accordingly, it is important to highlight that only experienced surgeons are predisposed to use this kind of ball-shaped instrument.
1.2. Robotic-Assisted Craniotomy

Despite the increasing number of surgical robotic systems appearing in recent decades, only a small number of robotic assistant systems for craniotomy have appeared in the literature. The first robotic system for craniofacial surgery was proposed in 1998, adapting an industrial manipulator for the application [5]. “Neurobot”, a robot developed for craniotomy, was reported a few years later [6]. In 2003, an anthropomorphic robot was adapted for otoneurosurgery, enhancing the control of the interactions between the drill and the patient’s skull [7]. A robotic system called RobaCKa, combining a commercial CASPAR robot and an optotronic navigation system, was the first system tested on real patients during craniotomy surgery [8]. A parallel robot based on a Stewart platform was also proposed for craniotomy in [9] by including a prismatic joint holding the surgical drill at the mobile platform. In [10], a new dedicated mechanism decoupling position and orientation motion was used for craniotomy procedures using simulated plastic skulls. “CRANIO”, a dedicated robotic system, was also experimentally tested, as reported in [11]. Furthermore, a robotic system for keyhole craniotomy was presented in [12], based on reconfigurable hexapod kinematics and directly fixed to the patient’s head. Few mechanisms have also appeared in recent years, including a specific kinematic constraint known as the Remote Center of Motion (RCM). In [13], a hybrid mechanism decoupling two angular motions was presented. Finally, a Spherical Parallel Mechanism (SPM) for craniotomy was recently presented in [14], including optimized kinematics to guarantee highly kinematic performances.

1.3. Objectives and Summary

In the literature, most robotic manipulators dedicated to craniotomy are based on classical industrial architectures (anthropomorphic or hexapod). A recent trend seems to favor more dedicated architectures based on RCM. According to the requested craniotomy Degrees of Freedom (DoF), two rotations, an SPM is proposed to handle the drilling tool. This type of architecture is known for generating RCM kinematics. This mechanism has a total of three angular DoF that allow one degree of redundancy. The contribution of this work focuses first on the experimental analysis of the craniotomy surgery task. Secondly, the redundancy of the SPM is used as an advantage by using the spinning motion as a reconfiguration variable in order to improve the parallel robot behavior. The present method simply relies on identifying the redundant configuration that will generate the minimum torque for each point of a preplanned trajectory. It is assumed that a craniotomy trajectory on the patient’s skull will be planned during the preoperation phase. A simulation will then allow determining how the SPM shall generate this trajectory. A specific strategy is used to determine the reconfiguration to minimize the motor torques while generating enough reaction force to drill the patient’s skull. In the current research work, an experimental campaign of motion capture and force recording is conducted for the analysis of the kinematic and force interaction characterizing Burr hole craniotomy procedures. These experimentations were carried out on a human cadaver to ensure a higher degree of realism. The collection of these data will allow the trajectory planning of robotic-assisted craniotomy using the SPM.

The rest of the study is organized as follows: Section 2 will describe the motion capture experiments that allowed determining the trajectory of the surgical drill. Section 3 illustrates how the collaborative robot was used to determine the magnitude of the skull reaction force. The strategy used to minimize the required torque to generate this force is detailed in Section 4. Finally, Section 5 presents the conclusion of this study.

2. Craniotomy Gesture Analysis

2.1. Work Environment

This section is dedicated to the description of the used experimental equipment and the procedure followed to record the surgeon’s gestures while performing a craniotomy. Hence, only the motion of the drilling tool handled by the surgeon is studied in the
present study. Figure 1 highlights the steps followed leading the tool orientations. Further information on the experimental setup can be found in [14].

![Figure 1](image_url)

**Figure 1.** Work environment and procedure followed to compute the drilling tool orientation.

Five tasks were identified in collaboration with the surgeon and recorded during the craniotomy surgery on the cadaver. Each task was defined by its specific location (i.e., left frontal, right frontal, left temporal, right temporal, middle) and was chosen according to the neurosurgeon’s recommendations. The five locations linked to the five tasks are shown in Figure 2 and represent the most important locations operated on during the craniotomy surgery.

![Figure 2](image_url)

**Figure 2.** Craniotomy surgery drilling location.

### 2.2. Motion Capture Results

The Euler angles were selected to define the drill orientation. Two angles were used: the drill rotated around the longitudinal axis and then rotated around the transverse axis. The drill orientation angles are defined by $\psi$ and $\theta$, as shown in Figure 3. These two angles were computed based on the marker coordinates installed on the surgical drill $D_{r1}$ and $D_{r3}$.

The orientation angles were computed according to the following equations, with $D_{r13} = D_{r3} - D_{r1}$:

\[
\theta = \cos^{-1}\left(\frac{D_{r13}}{\|D_{r13}\|} \cdot \mathbf{z}\right) \tag{1}
\]

\[
\psi = \text{ATAN2}\left(\frac{D_{r13}}{\|D_{r13}\| \cdot \sin \theta} \cdot \mathbf{y}, -\frac{D_{r13}}{\|D_{r13}\| \cdot \sin \theta} \cdot \mathbf{x}\right) \tag{2}
\]
For this purpose, we used the MoCap system to measure the surgeon’s gestures during the task execution by computing the orientation angles of the drilling instrument, as shown in Figure 4. These latter allow evaluating the workspace size during each task. Concerning these measurements, it is important to mention that the outliers are indicated individually using the “+” symbol in red.

Figure 4 shows the distribution of the drilling tool orientation angles $\theta \in \mathbb{R}$ and $\psi \in \mathbb{R}$ and Euler angles. The horizontal edges of the blue rectangle represent the interquartile range (i.e., 25th to the 75th percentile). The red lines represent the median (Q2/50th percentile) (i.e., the middle value of the dataset). The black lines represent the first quartile (Q1/25th percentile) (i.e., the middle number between the smallest number and the median of the dataset) and the third quartile (Q3/75th percentile) (i.e., the middle value between the median and the highest value of the dataset, respectively). Measures of orientation angles (3230 for left frontal and right temporal, respectively) were analyzed during the drilling tasks. Mean $\theta$ was higher for left frontal (mean of 17.98°, interquartile range: 13.34–21.76) than right temporal (mean of 14.76°, interquartile range: 12.99–17.07), while mean $\psi$ was lower for right temporal (mean of −76.64°, interquartile range: −77.43–−67.43) than for left frontal (mean of 66.35°, interquartile range: 63.49–71.03).
3. Craniotomy Interaction Forces Measurements

3.1. Forces Reconstruction through Torque-Based Cobot

In addition to the motion, the interaction effort was investigated in this following experimental setup. As shown in Figure 5, a collaborative robot (cobot), 7-DoF Franka Robot, was used to perform the drilling task while measuring the interaction efforts between the drilling tool and the anatomic tissue. For this purpose, the surgeon used a master device (3-DoF Novint Falcon) to control the cobot holding the drilling tool through a teleoperation control mode. The interaction efforts between the drilling tool and the anatomic tissue were calculated using the measurements of the joint robot external torques. The control architecture of the teleoperation platform is presented in the next section.

![Drilling task performed by the cobot in teleoperation mode. The joint external torque sensors of the robot are used to calculate the 6-axis interaction forces \( F_{\text{ext}} = [f_x, f_y, f_z] \) and torques \( T_{\text{ext}} = [\tau_x, \tau_y, \tau_z] \) between the drilling tool and the anatomic tissue.](image)

**Figure 5.** Drilling task performed by the cobot in teleoperation mode. The joint external torque sensors of the robot are used to calculate the 6-axis interaction forces \( F_{\text{ext}} = [f_x, f_y, f_z] \) and torques \( T_{\text{ext}} = [\tau_x, \tau_y, \tau_z] \) between the drilling tool and the anatomic tissue.

As mentioned above, the robotic system allows the surgeon to control the translational movements of the drilling tool held by the cobot by operating the Novint Falcon device. The rotational movements are also controlled by the surgeon by pressing buttons on the Novint Falcon device’s ball grip. The control architecture for the proposed robot assistant is shown in Figure 6. We propose to define a task-space compliance control strategy. The compliance feature is suitable for smoothing the robot’s movements, avoiding sudden gestures. Thus, let us define the torque control input \( T_i \in \mathbb{R}^{7 \times 1} \) as follows:

\[
T_i = T_L + \mathbf{H}(\mathbf{q}_{\text{curr}}, \dot{\mathbf{q}}_{\text{curr}})
\]  

where the torque control vector \( T_L \in \mathbb{R}^{7 \times 1} \) implementing the drilling tool motion task is defined as:

\[
T_L = \mathbf{J}^T \left[ \mathbf{K}_p (\mathbf{x}_{\text{des}} - \mathbf{x}_{\text{curr}}) - \mathbf{K}_d \dot{\mathbf{x}}_{\text{curr}} \right]
\]  

The cartesian desired pose \( \mathbf{x}_{\text{des}} \in \mathbb{R}^{6 \times 1} \) is composed of the desired position and orientation values sent by the Novint Falcon device. The current cartesian position and velocity are represented by \( \mathbf{x}_{\text{curr}}, \dot{\mathbf{x}}_{\text{curr}} \in \mathbb{R}^{6 \times 1} \). Moreover, the torque input compensates for the inertial and dynamic effects by including an estimation of the Coriolis, centrifugal and gravity compensation torques \( \mathbf{H}(\mathbf{q}_{\text{curr}}, \dot{\mathbf{q}}_{\text{curr}}) \in \mathbb{R}^{7 \times 1} \), calculated according to the current joint position and velocity vectors \( \mathbf{q}_{\text{curr}}, \dot{\mathbf{q}}_{\text{curr}} \in \mathbb{R}^{7 \times 1} \). Because control law (4) works in the manner of a damper–spring system, where the degree of compliance is regulated along...
each axis (in position and orientation) by the choice of the cartesian stiffness diagonal matrix $\mathbf{K}_{p_d} \in \mathbb{R}^{6 \times 6}$ and the cartesian damping diagonal matrix $\mathbf{K}_{d_d} \in \mathbb{R}^{6 \times 6}$. This latter calculated according to the desired damping ratio $\zeta_d$ [15].

![Diagram](image)

Figure 6. Teleoperation platform with force feedback.

Communication between the Novint Falcon device and the Franka robot was established using a USB protocol and a User Datagram Protocol (UDP), where the frequency rates for the robot’s controller and the Falcon laptop were 1 kHz and 0.03 kHz, respectively. Moreover, Robot Operating System (ROS) middleware was used to develop the global control framework, enhancing the ease of communication between the different components of the platform.

3.2. Experimental Results

Each joint of the Franka robot was equipped with a torque sensor measuring the external torques generated by the contact with the skull. The external torques $\mathbf{\tau}_{ext} \in \mathbb{R}^7$ were projected to the Cartesian space through the Jacobian matrix $\mathbf{J} \in \mathbb{R}^{6 \times 7}$, obtaining the contact forces/torques $\mathbf{F}_{ext} = \begin{bmatrix} \mathbf{F}_{ext_p} \mathbf{F}_{ext_r} \end{bmatrix} \in \mathbb{R}^6$ between the drilling tool and the skull as follows:

$$\mathbf{F}_{ext} = \left( \mathbf{J}^T \right)^+ \mathbf{\tau}_{ext} \tag{5}$$

where $\mathbf{F}_{ext_p} = [f_x, f_y, f_z] \in \mathbb{R}^3$ are the contact forces along the cartesian axes, whereas $\mathbf{F}_{ext_r} = [\tau_x, \tau_y, \tau_z] \in \mathbb{R}^3$ are the contact torques around the cartesian axes. Using the teleoperated system, we performed several experimental craniotomy drilling tests on the cadaver. The aim of these tests was to detect the maximum tangential interaction force between the drilling tool and the skull. Based on Figure 6, the tangential interaction force is calculated as $f_{tang} = \sqrt{f_x^2 + f_y^2}$. Figure 7 depicts the measured tangential force values during the most significant tests. It can be noted that the maximum tangential force was recorded in Trajectory 3, with a maximum force magnitude of 12.96 N. In addition, Figure 8 shows the distribution of the interaction forces $f_{tang}$ over five surgical tests. Measures of forces by the cobot (2993, 2673, 4446, 5980 and 5590 for the five trajectories, respectively) were analyzed during surgical tests performed on the cadaver. Mean $f_{tang}$ was the lowest for Traj2 (mean of 1.45 N, interquartile range: 0–2.95) and the highest for Traj3 (mean of 3.84 N, interquartile range: 0–12.96).
In order to perform the craniotomy, an SPM was studied. This type of architecture is known for generating RCM kinematics as its end effector rotates around the Center of Rotation (CoR). This mechanism has a total of three angular DoF: the end effector rotates with two angles and can spin around an axis passing through its center and the CoR. In the present study, a 3-DoF mechanism is proposed to perform a task that requires only two DoF. The idea is to use the last DoF (the spinning motion) as a reconfiguration variable to improve the behavior of the mechanism in the same position. Indeed, as the end effector is supposed to hold a surgical drill, the spinning motion of the end effector will generate a rotation of the drill around its longitudinal axis. This motion will have no impact on the operation of the drill itself. However, it will alter the configuration of the mechanism as illustrated in Figure 8a and, therefore, modify its behavior.

The mechanical architecture proposed is a 3-RRR SPM. It is a parallel mechanism that connects its base with its end effector using three identical RRR legs. Each leg is mounted with three revolute joints and two spherical linkages. The linkages are dimensioned by the angle between the revolute joint axes. The first revolute joint of each leg is active, and their rotation serves as the mechanism’s input coordinates. A kinematic representation of the mechanism is shown in Figure 8b. As the three RRR legs are identical, the dimension of

**Figure 7.** Tangential interaction forces $f_{\text{tang}}$ measured by the cobot during the surgical tests performed on the cadaver.

**Figure 8.** (a) Illustration of the 3-RRR SPM reconfigurability. (b) Kinematic representation of the 3-RRR Spherical Parallel Mechanism.

4. Craniotomy Trajectories by the Spherical Parallel Mechanism

4.1. Kinematic and Static Analysis of the SPM

In order to perform the craniotomy, an SPM was studied. This type of architecture is known for generating RCM kinematics as its end effector rotates around the Center of Rotation (CoR). This mechanism has a total of three angular DoF: the end effector rotates with two angles and can spin around an axis passing through its center and the CoR. In the present study, a 3-DoF mechanism is proposed to perform a task that requires only two DoF. The idea is to use the last DoF (the spinning motion) as a reconfiguration variable to improve the behavior of the mechanism in the same position. Indeed, as the end effector is supposed to hold a surgical drill, the spinning motion of the end effector will generate a rotation of the drill around its longitudinal axis. This motion will have no impact on the operation of the drill itself. However, it will alter the configuration of the mechanism as illustrated in Figure 8a and, therefore, modify its behavior.

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Figure 9. (a) Construction of the SPM base. (b) Kinematic of the SPM end effector.

The resolution of the Inverse Kinematic Model (IKM) of this type of SPM is well documented in the literature [16], and it can be written as follows:

\[ z_{k2} \cdot z_{k3} = \cos \beta, \]  

(6)

With \( k = A, B \) or C. This model must be solved for each leg of the SPM. Deriving Equation (6) consists of calculating the coordinates of axes \( z_{k2} \) and \( z_{k3} \) for each leg as follows:

\[
\begin{align*}
    z_{A2} &= R_y(\lambda)R_z(\theta_A)R_y(\alpha)z \\
    z_{B2} &= R_z(-2\pi/3)R_y(\lambda)R_z(\theta_B)R_y(\alpha)z, \\
    z_{C2} &= R_z(2\pi/3)R_y(\lambda)R_z(\theta_C)R_y(\alpha)z \\
    z_{A3} &= M_E(\psi, \theta, \varphi)R_y(\gamma)z \\
    z_{B3} &= M_E(\psi, \theta, \varphi)R_z(-2\pi/3)R_y(\gamma)z, \\
    z_{C3} &= M_E(\psi, \theta, \varphi)R_z(2\pi/3)R_y(\gamma)z
\end{align*}
\]

(7)  

(8)

where \( R_\theta(\varepsilon) \) is a rotation matrix of angle \( \varepsilon \) around axis \( u \). The orientation of the mechanism end effector is given by the rotation matrix \( M_E \). For each leg, the literal expressions of all involved joint axes \( z_{k2} \) and \( z_{k3} \) coordinates are calculated and substituted into Equation (6). Then, the dot product of the developed expression will lead to an equation in the form where the active joint variable is isolated:

\[ L_k \cos \vartheta_k + M_k \sin \vartheta_k = N_k, \]

(9)

where \( L_k, M_k \) and \( N_k \) are literal expressions that include the end-effector coordinates \( \psi, \theta \) and \( \varphi \) and the mechanism linkage dimensions \( \alpha, \beta \) and \( \gamma \). Their only function is to reduce the proximal and distal spherical linkages is given by the angles \( \alpha \) and \( \beta \), respectively. The size of the end effector is given by the angle \( \gamma \), which is measured between its center axis and the last revolute joint of any leg. The joint input coordinates are measured at the first revolute joint of each leg as \( \theta_k \), with \( k \) referring to the leg considered (\( k = A, B \) or \( C \)).

For each leg \( k \), all joints are represented by axes \( z_{ki} \), with \( i \) referring to the joint position on the leg. The mechanism base is represented by the axes of the three active revolute joints \( z_{A1}, z_{B1} \) and \( z_{C3} \). They are disposed as a regular trihedron so that the axis \( z_0 \) of the origin reference frame is equidistant for all \( z_{ki} \) axes as shown in Figure 9a. The angle \( \lambda \) measured between the axes \( z \) and \( z_{A1} \) is adjusted so that all \( z_{ki} \) axes form another reference frame. This specific disposition will ensure that the mechanism end effector is located at the origin reference frame at the home position. The end effector is rotated around the mechanism CoR with three DoF. Its motion is defined as three successive rotation of angles \( \psi, \theta \) and \( \varphi \) (in this order) around the axes \( z, x \) and \( z \), respectively, as illustrated in Figure 9b.
the size of the equations. This leads for each leg to the following expression of the active joint coordinate:

\[
\theta_k = \cos^{-1} \left( N_k / \sqrt{L_k^2 + M_k^2} \right) + \arctan2(M_k, L_k),
\]

(10)

The details of the resolution method can be found in [16].

The static model of the mechanism can be determined using its Jacobian matrix as follows:

\[
\tau = J^T f,
\]

(11)

With \( \tau \) a vector containing the joint torques \( \tau_A, \tau_B \) and \( \tau_C \) and \( f \) the force expressed in the end-effector reference frame. The SPM Jacobian matrix can be found by differentiating the IKM given by Equation (6). Then, it can be written in a matrix form that gives the relationship between the joint velocities \( q \) and the end-effector velocity \( \omega \) as:

\[
Bq = A \omega,
\]

(12)

where \( A \) and \( B \) can be determined using the revolute joint axes coordinates as followed:

\[
A = \begin{bmatrix}
(z_{A2} \times z_{A3})^T \\
(z_{B2} \times z_{B3})^T \\
(z_{C2} \times z_{C3})^T
\end{bmatrix}, \quad B = \begin{bmatrix}
z_{A1} \times z_{A2} \times z_{A3} & 0 & 0 \\
0 & z_{B1} \times z_{B2} \times z_{B3} & 0 \\
0 & 0 & z_{C1} \times z_{C2} \times z_{C3}
\end{bmatrix}.
\]

(13)

The mechanism Jacobian matrix \( J \) can then be calculated as:

\[
J = A^{-1} B.
\]

(14)

Based on the mechanism’s static model, it is possible to calculate the joint torques required to generate a force of a given direction and magnitude for a given configuration of the mechanism.

4.2. Torque Minimization Strategy

It is planned that while the robotic manipulator performs the trajectory for craniotomy, its reconfigurability will be used to improve its behavior. One of the major aspects in the robotization of craniotomy is to ensure that the manipulator can generate enough force to drill the skull in Section 2. In the present study, the skull reaction force is assumed to remain tangential to the skull surface and in the direction of the cutting. Its maximum magnitude was identified through the experiments on the human cadaver presented in Section 3.2. Based on the kinematic and static models presented in Section 4.1, the required input joint coordinates and torques to perform these trajectories can be determined. Both models are implemented on a MATLAB program that uses as input the magnitude of the skull reaction force and the angular motion of the surgical drill. The direction of the reaction force is determined by the trajectory of the drill. As an example, the input joint coordinates \( \theta_k \) and torques \( \tau_k \) obtained for a recorded trajectory are displayed in Figure 10.

In this example, the magnitude of the reaction force is set to 1 N, and the spinning angle \( \varphi \) of the end effector is purposely maintained to zero in order to illustrate the performance of the mechanism when its reconfigurability is not used.

The present strategy is to determine the end-effector spinning angle that will minimize the torques for a given position \( (\psi, \theta) \). For each point of a recorded trajectory, the measured end-effector position and the force are extracted. Then, the corresponding input joint coordinates and torque are calculated for an end-effector spinning angle varying in an interval between preset values \([\varphi_{\text{min}}, \varphi_{\text{max}}] \). For each spinning angle, the average of the three torque \( \tau_{AV} \) is calculated. Then, the minimum value \( \tau_{OPT} \) is saved, and the corresponding spinning angle \( \varphi_{OPT} \) is collected. This strategy is implemented on a new MATLAB program and is tested on the same recorded trajectory used in Figure 10. As a
result, it can be seen in Figure 11a that on the same trajectory, the input coordinates are different. This means that the mechanism will modify its configuration as it searches to minimize its torque average. As displayed in Figure 11b, the torque average was reduced compared to the classical trajectory where the spinning angle is maintained to zero.

![Calculated input coordinates on trajectory](image1)

![Calculated torques on trajectory](image2)

Figure 10. (a) Input joint coordinates calculated for a trajectory with a fixed spinning angle. (b) Torques calculated for the same trajectory.
three torque $\tau_{AV}$ is calculated. Then, the minimum value $\tau_{OPT}$ is saved, and the corresponding spinning angle $\phi_{OPT}$ is collected. This strategy is implemented on a new MATLAB program and is tested on the same recorded trajectory used in Figure 10. As a result, it can be seen in Figure 11a that on the same trajectory, the input coordinates are different. This means that the mechanism will modify its configuration as it searches to minimize its torque average. As displayed in Figure 11b, the torque average was reduced compared to the classical trajectory where the spinning angle is maintained to zero.

Figure 11. (a) Input joint coordinates required for the minimization of the torque average. (b) Resulting torque average using the mechanism reconfigurability.

4.3. Results and Discussions

The MATLAB program was executed for the trajectories that were recorded during the experiments on the cadavers presented in Section 2. The mechanism used for these simulations has the linkage dimensions arbitrarily set to $(\alpha \beta \gamma) = (45\ 40\ 30)$. Based on the measurements of Section 3.2, the magnitude of the reaction force is set to 13 N. The program will calculate the torques required to generate this force for a spinning angle from $-\pi$ to $\pi$. 

![Diagram of input coordinates and average torque comparison](image-url)
For all trajectories, the resulting average torque with and without the reconfigurability are used to determine the average torque reduction ratio. These are all displayed in Figure 12.

**Figure 12.** Average torque reduction ratio provided by the mechanism of reconfigurability on craniotomy trajectories.

The detailed results of all simulations are given in Table 1. The results show that the torque average is significantly reduced on all trajectories by 21.4 to 99.7%. What does not appear in Table 1, however, is the individual torques calculated on the trajectories with and without the reconfigurability feature. The present simulations revealed that when optimized, the maximum values of individual torque vary from 1.86 to 4.34 Nm compared to 4.39 to 16.75 Nm when the reconfigurability is not used. This means that considering the trajectories recorded on the experiments on cadavers, the present method allows reducing the torque requirement from 16.75 to 4.34 Nm (74.1%) for the motorization of the robotic manipulator.

**Table 1.** Average torque reduction given by the mechanism’s reconfigurability.

| Trajectories | Original Torque Averages (Nm) | Optimized Torque Averages (Nm) | Reduction (%) |
|--------------|-------------------------------|-------------------------------|---------------|
|              | Min                           | Max                           | Min           | Max           | Min       | Max       |
| 1            | 3.32                          | 3.51                          | 1.05          | 1.18          | 66.4      | 68.7      |
| 2            | 3.65                          | 6.02                          | 0.11          | 0.72          | 80.4      | 98.2      |
| 3            | 2.82                          | 2.85                          | 1.76          | 2.22          | 21.4      | 38.6      |
| 4            | 2.75                          | 2.87                          | 0.08          | 1.03          | 63.9      | 97.3      |
| 5            | 3.41                          | 3.65                          | 0.04          | 0.87          | 74.9      | 98.9      |
| 6            | 3.37                          | 3.70                          | 1.07          | 1.55          | 56.6      | 68.3      |
| 7            | 2.80                          | 2.87                          | 1.65          | 1.77          | 37.2      | 41.9      |
| 8            | 6.05                          | 14.47                         | 0.04          | 0.71          | 88.8      | 99.7      |
| Total        | 2.75                          | 14.47                         | 0.04          | 2.22          | 21.4      | 99.7      |

It can be seen that there is no discontinuity on the evolution of the collected spinning angle displayed in Figure 13. This shows that a robotic manipulator based on a 3-RRR SPM can be smoothly controlled to generate craniotomy trajectories that minimize the
required torques. The main limitation of the present study is that the effect of gravity on the calculated torques is not taken into consideration. Indeed, the general orientation of the robotic manipulator on the patient’s skull remains uncertain at the moment.

| Trajectory | Spinning Angle (°) | Spinning Torque (Nm) |
|------------|--------------------|----------------------|
| 1          | 3.37               | 3.70                 |
| 2          | 3.37               | 3.70                 |
| 3          | 1.07               | 1.55                 |
| 4          | 56.6               | 68.3                 |
| 5          | 2.80               | 2.87                 |
| 6          | 1.65               | 1.77                 |
| 7          | 37.2               | 41.9                 |
| 8          | 6.05               | 14.47                |
| Total      | 2.75               | 14.47                |

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Figure 13. Evolution of the end-effector spinning angle for the minimization of the average torques.

5. Conclusions

A robotic manipulator dedicated to craniotomy with a remote center of motion based on a Spherical Parallel Manipulator (SPM) architecture was presented in this paper. The SPM was proposed to handle the drilling tool through the requested craniotomy Degrees of Freedom (DoF) with two rotations, allowing one degree of redundancy according to the total DoF. Two main contributions were proposed in this paper. Firstly, an experimental analysis of craniotomy surgery tasks was presented. Secondly, the behavior of the proposed architecture was improved, taking advantage of the redundancy of the SPM using the spinning motion as a reconfiguration variable. Thus, a minimization of the motor torque was achieved based on the reconfiguration feature through the spinning angle modulation, while generating enough reaction force to drill the patient’s skull. Moreover, an experimental campaign of motion capture and force recording was conducted for the analysis of the kinematic and force interaction characterizing Burr hole craniotomy procedures. These experimentations were performed by a neurosurgeon on a human cadaver, ensuring highly realistic conditions.

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