Gravity Compensation for the Galen: Paper Presentation

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Project Summary

Improve performance of the Galen Microsurgical system:

- Implement tool gravity compensation for static tools
- Implement tool gravity compensation for tools in motion
- Characterize and account for deflection

Papers Selected

The robotic ENT microsurgery system: A novel robotic platform for microvascular surgery

Why: Demonstrates a relevant use case for the Galen system.

Tool Gravity Compensation for Maneuverability Enhancement of Interactive Robot Control for Bone Fracture Reduction System.

Why: Directly related to the problem we are trying to solve.

Gravity compensation and compliance based force control for auxiliarily easiness in manipulating robot arm
Why: Also related to the gravity compensation problem

The robotic ENT microsurgery system: A novel robotic platform for microvascular surgery.

Summary:

- Tested effectiveness of the REMS system for microvascular surgery
- Developed a tremor rating scale for microvascular surgery (MTS)

Results:

- There was significantly less tremor for naive users
- Slightly less Time to Complete for naive users
- Inter-rater reliability for MTS was good, having an intraclass correlation coefficient over .9

Significance

The paper showed that the REMS is capable of performing microvascular surgeries, which other robotic surgical systems such as the DaVinci are not well suited for.

User feedback suggested that the REMS was more stable and generally preferable over freehand surgery for naive users. This suggested that the REMS could ease the learning curve associated with microvascular surgery.

The expert finished quicker freehand, and had around the same tremor score between the REMS and freehand.

Experiment

For this experiment, 6 naive participants and 1 expert performed a microvascular anastomosis on a chicken thigh model, using both feedhand and the REMS.

Feng, et al.

Experiment

Each Trial was recorded for blinded grading of tremors and Time to Completion by 7 independent microvascular experts using MTS

MTS determines severity of a tremor based on the amplitude of the tool tip compared to the vessel width.

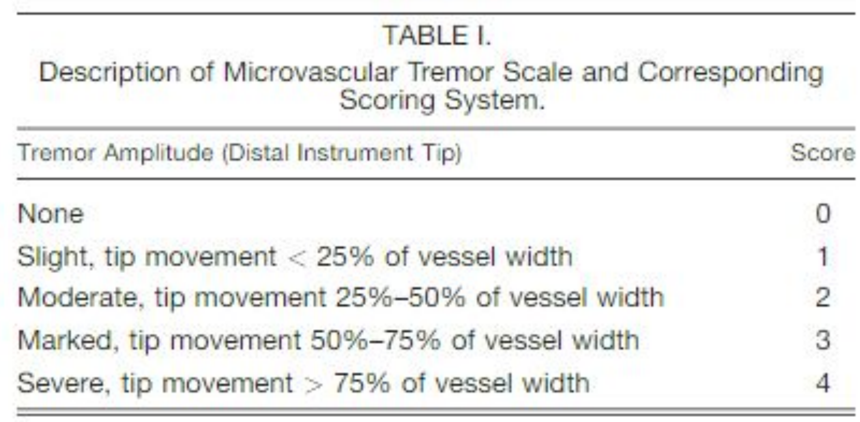

TABLE I.

Description of Microvascular Tremor Scale and Corresponding Scoring System.

Tremor Amplitude (Distal Instrument Tip)	Score
None	0
Slight, tip movement < 25% of vessel width	1
Moderate, tip movement 25%–50% of vessel width	2
Marked, tip movement 50%–75% of vessel width	3
Severe, tip movement > 75% of vessel width	4

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Results

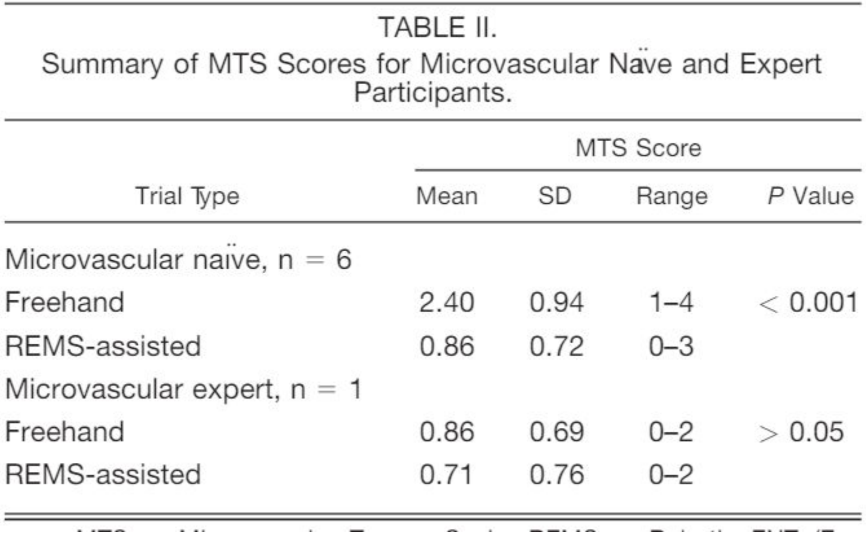

TABLE II.
Summary of MTS Scores for Microvascular Naïve and Expert Participants.

	MTS Score			
Trial Type	Mean	SD	Range	*P* Value
Microvascular naïve, n = 6				
Freehand	2.40	0.94	1–4	< 0.001
REMS-assisted	0.86	0.72	0–3	
Microvascular expert, n = 1				
Freehand	0.86	0.69	0–2	> 0.05
REMS-assisted	0.71	0.76	0–2	

Feng, et al.

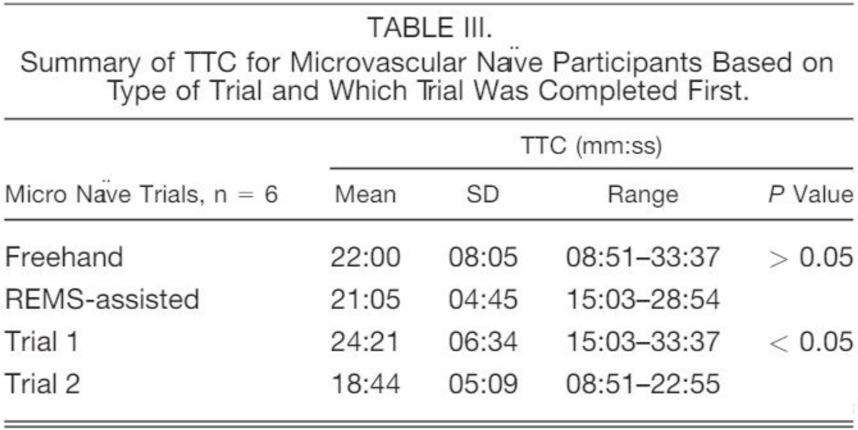

TABLE III.
Summary of TTC for Microvascular Naïve Participants Based on Type of Trial and Which Trial Was Completed First.

	TTC (mm:ss)			
Micro Naïve Trials, n = 6	Mean	SD	Range	*P* Value
Freehand	22:00	08:05	08:51–33:37	> 0.05
REMS-assisted	21:05	04:45	15:03–28:54	
Trial 1	24:21	06:34	15:03–33:37	< 0.05
Trial 2	18:44	05:09	08:51–22:55	

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Thoughts

Next steps:
Redoing the study with more intermediate users to see how TTC and tremor is affected.
See how well the system works on even smaller scale procedures.
Implementing and getting feedback for additional features such as virtual fixtures

Critique:
Mentioned a metric called TTS but did not describe what that was
Mentioned how the first trial took more time on average than the second regardless of whether it was feedhand or REMS.

Tool Gravity Compensation for Maneuverability Enhancement of Interactive Robot Control for Bone Fracture Reduction System

Summary

- Presents work on an ongoing bone fracture reduction robotic system
- Used a knob connected to a 6DOF F/T sensor to position the system
- Created an analytical approach to tackle gravity compensation

Results:

- They found that their model was effective at removing gravity based disturbances in the F/T readings.

Significance

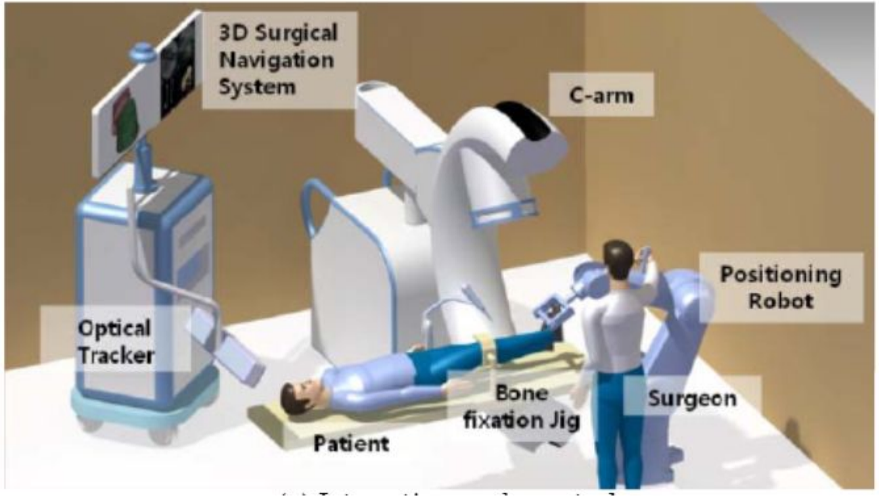
When long bones fracture and need to be surgically repaired, they have to be aligned and supported by several assistant surgeons during the operation. This is physical fatiguing and also exposes these surgeons to excess radiation.

Perfect use case for a robotic system to implemented.

Robot Assisted Bone Fracture Reduction System

System includes:

- A positioning robot
- A drilling robot
- A 3D surgical navigation system
- A C-arm
- An optical tracking system



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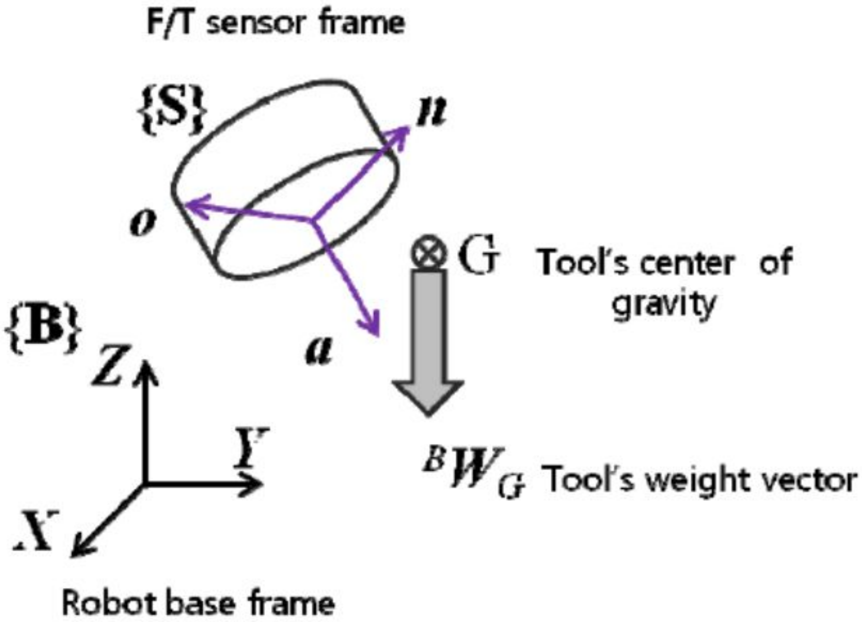
Gravity compensation approach

$$\mathbf{F}_{\text{measured,unbiased}} = \mathbf{F}_{\text{tool gravity}} + \mathbf{F}_{\text{interaction}}$$

$$\mathbf{M}_{\text{measured,unbiased}} = \mathbf{M}_{\text{tool gravity}} + \mathbf{M}_{\text{interaction}}$$

$$\begin{bmatrix} {}^{S}\mathbf{F}_{\text{tool gravity}} \\ {}^{S}\mathbf{M}_{\text{tool gravity}} \end{bmatrix} = \begin{bmatrix} {}^{S}_{B}\mathbf{R} & 0_{3\times 3} \\ {}^{S}\mathbf{p}_{G}\times {}^{S}_{B}\mathbf{R} & {}^{S}_{B}\mathbf{R} \end{bmatrix} \begin{bmatrix} {}^{B}\mathbf{W}_{G} \\ {}^{B}\mathbf{M}_{G} \end{bmatrix}$$



$${}^{S}\mathbf{p}_{G}\times = \begin{bmatrix} 0 & -p_z & p_y \\ p_z & 0 & -p_x \\ -p_y & p_x & 0 \end{bmatrix}$$

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Accounting for Bias

$$\mathbf{F}_{\text{measured,unbiased}} = \mathbf{F}_{\text{measured,biased}} + \mathbf{F}_{\text{compensating}}$$

$$\mathbf{M}_{\text{measured,unbiased}} = \mathbf{M}_{\text{measured,biased}} + \mathbf{M}_{\text{compensating}}$$

$$\mathbf{F}_{\text{compensation}} = [0, 0, -W_z]^T \qquad \mathbf{M}_{\text{compensation}} = [0, 0, 0]^T$$

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Results:

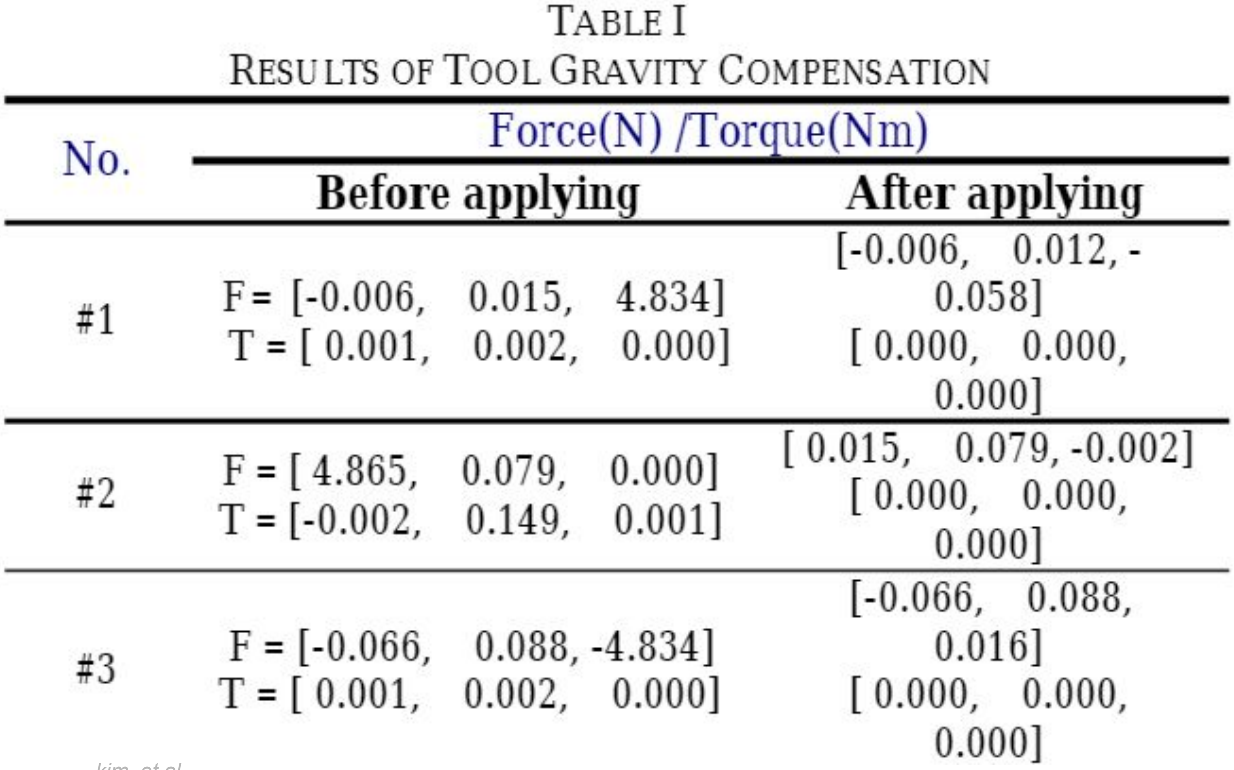

TABLE I
RESULTS OF TOOL GRAVITY COMPENSATION

No.	Force(N) /Torque(Nm)	
	Before applying	**After applying**
#1	F = [-0.006, 0.015, 4.834] T = [0.001, 0.002, 0.000]	[-0.006, 0.012, -0.058] [0.000, 0.000, 0.000]
#2	F = [4.865, 0.079, 0.000] T = [-0.002, 0.149, 0.001]	[0.015, 0.079, -0.002] [0.000, 0.000, 0.000]
#3	F = [-0.066, 0.088, -4.834] T = [0.001, 0.002, 0.000]	[-0.066, 0.088, 0.016] [0.000, 0.000, 0.000]

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Thoughts

Directly relevant to our project, as we are trying to compensation for tool gravity

Good empirical evaluation.

The paper did not go into much detail about their system. Did not talk about the type of optical tracking system

Gravity compensation and compliance based force control for auxiliarily easiness in manipulating robot arm.

Summary:

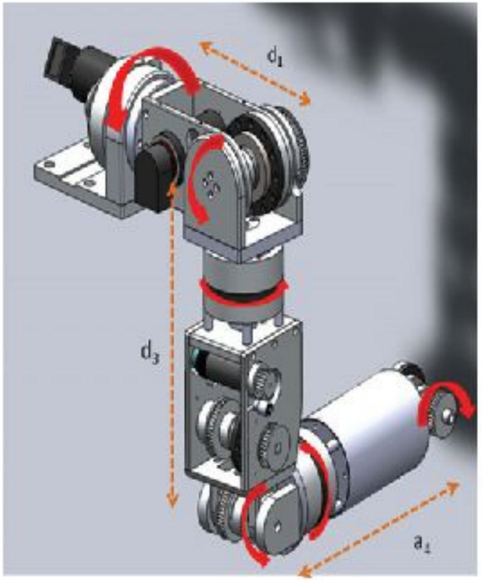
- Proposed a method using vector projection to calculate a general solution for gravity compensation at joints of robotic manipulator
- Developed an approach called force counterbalance control to balance external loads and retain dexterity

Results:

- Experimentally found that their methods were successful at retaining ease of use under an external force

Experimental Setup

They used a 6 DOF robotic arm connected to a PC



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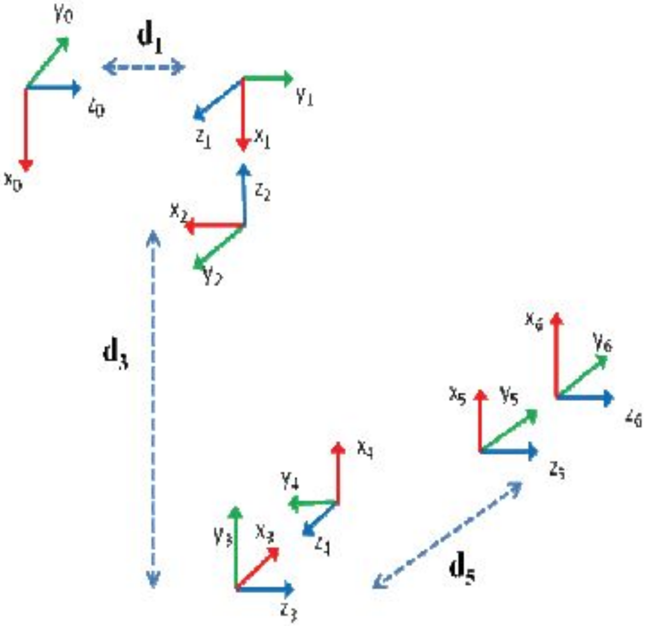

Gravity Compensation Technique

They use Denavit-hartenberg form to construct forward kinematics using coordinate transformations between joints

$$T_i^{i-1} = \begin{bmatrix} \cos\theta_i & -\sin\theta_i \cos\alpha_i & \sin\theta_i \sin\alpha_i & a_i \cos\theta_i \\ \sin\theta_i & \cos\theta_i \cos\alpha_i & -\cos\theta_i \sin\alpha_i & a_i \sin\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

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$$T_6^0 = T_1^0 \cdot T_2^1 \cdot T_3^2 \cdot T_4^3 \cdot T_5^4 \cdot T_6^5 = \begin{bmatrix} P_6^0 \\ 1 \end{bmatrix}$$

Gravity Compensation Technique

$$\tau = \vec{M} \cdot \vec{e} = [\vec{r} \times \vec{F}] \cdot \vec{e}$$

$$\vec{F}_i = m_i g \vec{i}$$

$$\vec{\tau} = \{[\vec{r} \times \vec{F}] \cdot \vec{e}\} \vec{e}$$

$$T^0_{r_i\;4\times4} = T^0_1 \cdot T^1_2 \cdots T^{i-1}_{r_i}, \vec{r}_i = \begin{bmatrix} T^0_{r_i}(1,4) \\ T^0_{r_i}(2,4) \\ T^0_{r_i}(3,4) \end{bmatrix}$$

$$R_{\theta_i} = \begin{bmatrix} \cos\theta_i & -\sin\theta_i & 0 \\ \sin\theta_i & \cos\theta_i & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$R_{\alpha_i} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha_i & -\sin\alpha_i \\ 0 & \sin\alpha_i & \cos\alpha_i \end{bmatrix}$$

$$e^0_i = R_{\theta_1} \cdot R_{\alpha_1} \cdot R_{\theta_2} \cdot R_{\alpha_2} \cdots R_{\theta_i} \cdot R_{\alpha_i} \cdot \vec{R}, R = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

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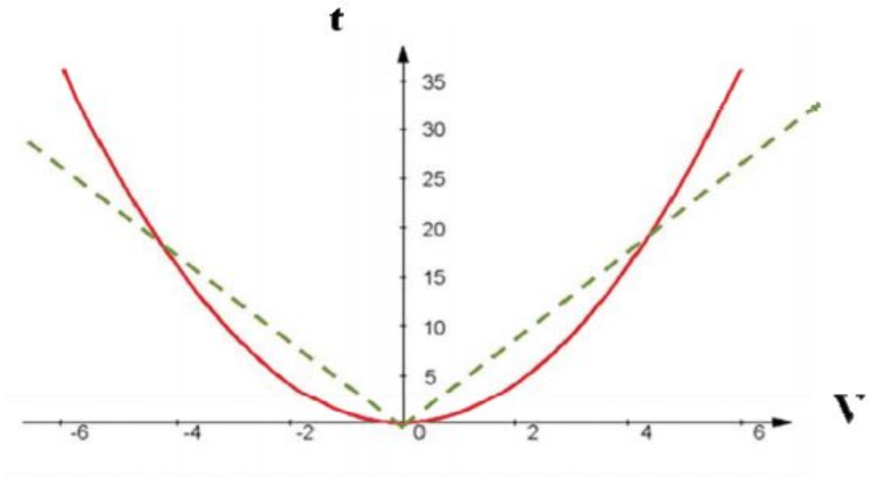
Auxiliary Torque Compensator

$$-M_f \Delta t + M_{external} \Delta t = I \Delta \omega$$



$$t = av^2 + k$$

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Critiques:

Riddled with grammatical errors

Experiment results did not have any empirical results, they just stated that it worked.

Bibliography:

Feng, Allen L., et al. “The robotic ENT microsurgery system: A novel robotic platform for microvascular surgery.” The Laryngoscope 127.11 (2017): 2495-2500.

Kim, Woo Young & Han, Sanghoon & Park, Sukho & Park, Jong-Oh & Ko, Seong Young. (2013). Tool Gravity Compensation for Maneuverability Enhancement of Interactive Robot Control for Bone Fracture Reduction System.

Luo, Ren C., Y. Yi Chun, and Yi W. Perng. “Gravity compensation and compliance based force control for auxiliarily easiness in manipulating robot arm.” Control Conference (ASCC), 2011 8th Asian. IEEE, 2011.