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| MECH 496 |
| Praxim: Techanical Analysis Report |
| Technical review of gravity compensation |
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| Gravity compensation has been revisited to assess the need for rotational gravity compensation mechanism for a four link uni-compartmental knee bone cutting device |

# Gravity Compensation

This section analyses gravity compensation techniques to be implemented on the device.

## Background

The goal of this technical analysis is to design a method to minimize the effect of unbalanced forces on the user experience of bone cutting while using the four linkage uni-compartmental knee bone cutting device. The device is required to limit the user input needed during operation to 2kg. This force is described as the operational weight of the device. Gravity compensation can be used to reduce the operation weight and consists of two components;

(1) The ability to impede the vertical motion of the tool with respect to the device bone mount

(2) The ability to impede device rotation about the joint located at the device bone mount

Early analysis suggested that 80% of users are satisfied if the force required to stabilize the device is approximately 1 kg. As a result, gravity compensation measures will be implemented to reduce the operation weight of the device to 10N. Figure 1 shows the user satisfaction curve for the operational weight of the device.

Figure : Plot of the predicted user satisfaction at different operational weights

# Rotational Gravity Compensation

Figure 2 shows an overview of the rotational gravity compensation problem. The joint located at the bone mount in Figure 2 is free to rotate about the y-axis. If the tool a distance Dx away from the bone mount joint the weight of the tool and surrounding links create a moment about the bone mount joint that the user must resist. A gravity compensation mechanism used to minimize this moment should apply a torque to the radial link that resists both clockwise and anticlockwise rotation without having significant impact on the feel of the device at the hard surface.

Gravity

Dx

Tool Weight

**LR:** Radial Links (combination of 4 rotational links that provide linear motion)  
**L3:** Vertical Offset Link  
**Dx:** Horizontal distance to bone mount joint

L3

LR

Bone Mount

θ R

θ23

Moment created at bone mount

x

z

Figure : Simplified linkage diagram for rotational gravity compensation

## Technical Analysis

In order to determine the torque needed to implement effective gravity compensation, the torque produced at different angles has been determined for the four linkage mechanism. A list of input variables used in the model is included in in Appendix B. The link lengths chosen fulfill all envelope requirements, and the link masses have been generated from the Solidworks model using 303 stainless steel. In the model the x component of the centre of gravity of each link with respect to the bone mount joint is determined and used to compute the moment about the bone mount joint at multiple tool positions and device orientations.

Three angles were varied in the analysis, (1) θR – the angle of the radial links with respect to the bone mount, (2) θ12 – the angle that varies the linear length of the radial links, and (3) θ54  - the angle of the tool link with respect to the horizontal plane. Plots for each are shown below and the red box highlights the predicted operating range for each link.

## Results

Figure 3 shows that the torque is largely symmetrical about the vertical plane - where θR = 0.The maximum torque generated around the bone mount joint with the operating range is 1.3 Nm, which corresponds to a user force of 9N. This value is based on the curve at 180 degrees, where the radial links are at full length and is not within the predicted operating range.

Gravity compensation, such as a resistive joint shown in Figure 4, could be implemented to reduce the torque at the extremes of the range. This reduction would shift the ideal – zero torque – operating zone away from the vertical position shown in Figure 3 to an intermediate position shown by the red circles in Figure 4. The exact zero torque position will vary with the length of the radial links. This scheme would also increase the torque when moving in the opposite direction to over 2Nm in some positions.

Operating Range for **θR**

Figure : Plot of torque with respect to θR at increments of θ12

Without gravity compensation

With gravity compensation

Ideal operating zone

Resistive Joint

Figure : Plot of torque with and without resistive joint gravity compensation

Figure 4 shows the torque generated about the bone mount and how it changes with the linear length of the radial joints. The maximum torque of 1.55Nm corresponds to the device position when the radial links are completely horizontal, and as in Figure 3 this position is not part of the predicted operating range. A resistive joint could be used to shift the curve downwards and reduce the total torque generated by half.

Operating Range for **θ12**

Figure : Plot of torque with respect to θ12 at increments of θR

Figure 5 shows the torque generated about the bone mount due to user motion along the y-axis. The maximum torque range of 0.2N is considerably smaller than that generated by the other two links. A resistive joint would not be beneficial for this joint.

Operating Range for **θ54**

Figure : Plot of torque with respect to θ54 at increments of θR

## Commentary

The figures above show that a resistive joint gravity compensation mechanism could effectively reduce maximum torque generated about the bone mount when moving away from the vertical position. Such a mechanism would likely come at the expensive of user feel because the force the user must provide will change direction throughout the operation, and the overall range of force the user must provide will increase.

The total effect of torque generated due to rotation about the bone mount is signifcant in comparison to both overall user satisfaction and the total weight of the linkages. At 80% user satisfaction the maximum for a user will implement is 10N, equal to the maximum force created due to the rotation effects. If no linear spring mechanism is used to impede the vertical motion of the tool with respect to the device bone mount, the maximum operating weight of the device will be approximately 1.8 kg corresponding to a user satisfaction of 20%. However the rotational forces and linear forces are maximized in different orientations, and will not affect the user at the sometime. As a result no rotation gravity compensation mechanism will be implemented on the device because overall satisfaction meets user requirements, but a vertical gravity compensation spring will be sized once prototype construction is complete. There will be safety issues because the joint is unrestrained that must be addressed before the device can be considered for human trials.

# Appendix A: Gravity Compensation Parameters

Table – List of input variables used for moment analysis

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| **INPUT VARIABLES** | |
| **LINK LENGTHS** | |
| length link 1 [m] | 0.07 |
| length link 2 [m] | 0.07 |
| length link 3 [m] | 0.05 |
| length link 4 [m] | 0.05 |
| length link 5 [m] | 0.07 |
| **LINK MASS** | |
| mass link 1 [kg] | 0.1 |
| mass link 2 [kg] | 0.1 |
| mass link 3 [kg] | 0.24 |
| mass link 4 [kg] | 0.25 |
| mass link 5 [kg] | 0.75 |
| **CONSTANTS** | |
| Gravity [m/s^2] | 9.81 |
| PI | 3.141593 |
| **LINK ANGLES** | |
| Theta 3R [deg] | 0 |
| Theta 34 [deg] | 0 |
| MASS TOOL | |
| mass tool [kg] | 0.635 |

Table – Table of maximum and minimum link ranges

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| --- | --- |
| Theta\_R | -45 to 45 |
| Theta\_12\_min | 30 |
| Theta\_12\_max | 120 |
| Theta\_5 | -45 to 45 |
| Theta\_3 | 20 |
| Theta\_3 | -15 |