Design of a novel 3DOF clinostat to produce microgravity for bioengineering applications

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Abstract— **This work presents the design of a novel 3DOF (3 Degrees of Freedom) clinostat to produce microgravity. Such a clinostat is novel because it does not contain an internal hatchery as other clinostats. This peculiarity is unique and allows this machine to produce better results in terms of a smaller microgravity generation. This 3DOF clinostat possesses a set of nonlinear dynamic equations that describe the partial accelerations of each DOF. The mean microgravity generated at the center of the clinostat can be computed using such partial accelerations. In this work, a microgravity of around 10^{-3} g has been achieved, which is a smaller microgravity generated by a RPM (Random Positioning Machine), which is also a clinostat. Results of this work are verified via intensive simulation studies in the form of graphs for different rotational frame speeds of the clinostat since this variable can substantially modify the desired outcomes. A smaller microgravity generator can be directly translated to a more accurate representation of true microgravity in outer space, producing a huge impact on bioengineering applications, since this clinostat allows performing outer space studies on earth with faithful results and with a minimum cost.**

I. INTRODUCTION

A clinostat is a machine that simulates an environment with microgravity in a small region of 3d (3-dimensional) space that looks like a sphere. This machine has several applications in bioengineering to test the behaviors generated from living organisms to low gravity exposure. These studies help on getting a better understanding on how organisms interact at an intracellular level.

This type of research can help find new ways to treat diseases such as cancer, leukemia or even normal flu, since there are lots of hints that suggest gravity acts as a switch that triggers most of the gene activities that takes place inside cells. Microgravity test help to identify such genes. For this reason, there has been a growing interest in performing these studies using RPM and clinostats, which are machines used to do these tests.

RPM machines are similar to clinostats in the way that both produce microgravity by averaging gravity. However, RPM machines base their movements in randomness, that is, those change the direction of rotation at random moments in time, causing mechanical stress (or artifacts) on the sample. For such a reason, RPM machines are not able to reproduce the same microgravity values.

On the other side, clinostats have the ability to perfectly reproduce results because of their constant rotational speeds, and their frames only rotate in one direction by design. Hence, in clinostats the artifacts on the samples become negligible. Generally, clinostats have two frames or 2DOF controlled by two motors, which is the minimum requirement to cover the region of a sphere, which is the best 3d-shape to simulate true microgravity environment.

In this work, a 3DOF clinostat will be analyzed. It is expected to obtain microgravity of around 10^{-3} g. In section II, the forward kinematics of the 3DOF clinostat is presented. The kinematics was manually calculated. Section III presents how the transposition of the gravity vector to the innermost frame is done. This stage is crucial to understand the behavior of the gravity-averaging technique. In section IV the equations to compute microgravity and its types in the samples are presented. Section V presents the microgravity values obtained in the simulations for different ratios of speed and positions in space around the center or rotation. Section VI presents some conclusions derived from this work as well as the future work related with the design and construction of a clinostat to generate optimal values of microgravity (about 10^{-3} g).

II. FORWARD KINEMATICS OF THE CLINOSTAT

The clinostat is a machine that generates rotations around the three axes by setting constant speeds on the motors. Generally, clinostats have two frames controlled by two motors, but in this work, we use three internal frames whose rotational speeds are controlled by each motor. Such an additional internal frame generates more complex movement patterns (analyzed in the following sections) and a set of more complicated equations that may derive in a heavier computational load for prolonged simulations.

Equation (1) corresponds to the rotation matrices between frames starting from the innermost frame 3 to the G or global frame, while equation (2) is the gravity vector in the G-frame

$$R_2^3 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad R_1^2 = \begin{bmatrix} -c_{\theta_3} & 0 & -s_{\theta_3} \\ -s_{\theta_3} & 0 & -c_{\theta_3} \\ 0 & -1 & 0 \end{bmatrix}$$

$$R_0^1 = \begin{bmatrix} c_{\theta_2} & 0 & -s_{\theta_2} \\ s_{\theta_2} & 0 & c_{\theta_2} \\ 0 & -1 & 0 \end{bmatrix} \qquad R_G^0 = \begin{bmatrix} 0 & c_{\theta_1} & -s_{\theta_1} \\ 0 & s_{\theta_1} & c_{\theta_1} \\ 1 & 0 & 0 \end{bmatrix} \quad (1)$$

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$$\vec{g}_G = \begin{bmatrix} 0 \\ 0 \\ -1 \end{bmatrix} \quad (2)$$

In Fig. 1, we can observe the schematic of the clinostat in its initial state. Matrices in (1) are obtained from the analysis of such a schematic. There are a total of five frames because we are taking into account the global G-frame and the frame that contains the sample into the clinostat, just in the center of the machine; the rest of the frames represent the orientation of each DOF of the clinostat and the rotation angles θ_1, θ_2, and θ_3 produced by each motor.

The G-frame contains the gravity vector $\vec{g}_G$ represented in (2) as a unity vector pointing in the negative direction of the Z axis. Using (1) and (2), we can compute the direction of $\vec{g}_G$ in any moment of time in the center of the clinostat.

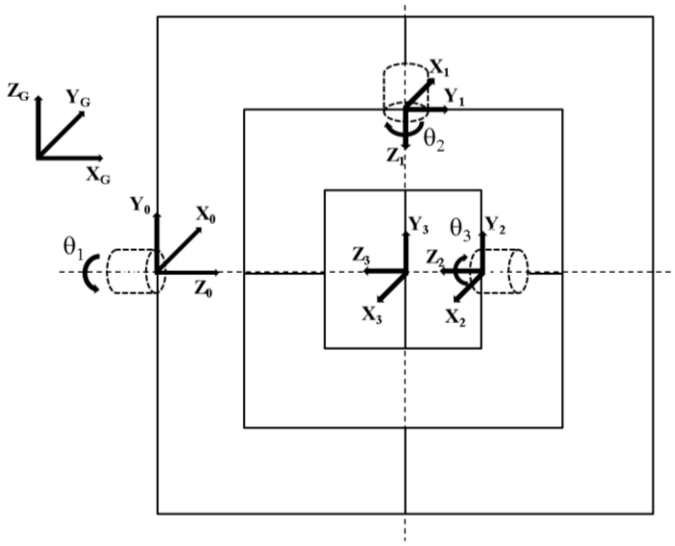

Fig. 1. 3DOF clinostat schematic.

III. GRAVITY VECTOR TRANSPOSITION

The next step is to transpose the gravity vector to the sample frame. This is done in (3) by multiplying the rotation matrices in the correct order

$$\vec{g}_3(t) = R_2^3 \, R_1^2 \, R_0^1 \, R_G^0 \, \vec{g}_G$$

$$\vec{g}_3(t) = \begin{bmatrix} c_{\theta_1} s_{\theta_3} - c_{\theta_2} c_{\theta_3} s_{\theta_1} \\ -c_{\theta_1} c_{\theta_3} - c_{\theta_2} s_{\theta_1} s_{\theta_3} \\ -s_{\theta_1} s_{\theta_2} \end{bmatrix} \quad (3)$$

The result shown in (3) indicates that gravity in frame 3 is time-dependent because the angles θ_1, θ_2, and θ_3 are also time-dependent. The frame rotation speeds can follow any set point value. In this case, for simulation simplicity, the rotational speed for each motor will remain constant.

IV. MICROGRAVITY DYNAMIC EQUATION

The sample located at the center of the clinostat has a certain size. When rotated, the sample covers a 3d sphere space of certain radius. If a point separated by a distance r from the center of the sphere moves tangentially around the sphere, then centrifugal and tangential forces appear that generate non-gravitational accelerations [1]. Such forces produce new accelerations to take into account when calculating the total microgravity. Thus, the equations that determine microgravity can be expressed as a sum of gravitational and non-gravitational accelerations, which are present in the sample at any instant of time.

In order to compute non-gravitational accelerations, we have to choose a radius. Several works agree that an appropriate radius for reliable simulation is 10 cm, because a radius located further away from the center of rotation generates bigger residual accelerations that could interrupt the nullification of gravity [1].

A. Gravitational Acceleration

The gravitational acceleration is calculated as the time-average of the gravitational accelerations for each axis of frame 3 as seen in (4), (5), and (6). Then, the vector sum of the partial accelerations is calculated as in (7).

$$G_{X_{mean}} = \frac{\sum_{i=1}^{n} g_{3x,i}}{n} \quad (4)$$

$$G_{Y_{mean}} = \frac{\sum_{i=1}^{n} g_{3y,i}}{n} \quad (5)$$

$$G_{Z_{mean}} = \frac{\sum_{i=1}^{n} g_{3z,i}}{n} \quad (6)$$

$$G_{mean} = \sqrt{\left(G_{X_{mean}}\right)^2 + \left(G_{Y_{mean}}\right)^2 + \left(G_{Z_{mean}}\right)^2} \quad (7)$$

B. Non-gravitational Acceleration

As mentioned before, this type of acceleration is caused by centrifugal and tangential forces that are generated further away from the center of rotation. Let $\vec{r}_3$ be a point in frame 3 as seen in (8) and $\vec{p}_{global}$ the position of $\vec{r}_3$ in the global frame as expressed in (9). Note that in (9), the rotation matrices have been transposed.

$$\vec{r}_3 = \begin{bmatrix} r_{3_x} \\ r_{3_y} \\ r_{3_z} \end{bmatrix} \quad (8)$$

$$\vec{p}_{global} = R_0^G \, R_1^0 \, R_2^1 \, R_3^2 \, \vec{r}_3 \quad (9)$$

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The speed of rotation of each motor is set to a constant. The rotational speed ratio between outer and inner frames containing the motors is set to 4:1.8, due to two reasons. First, such a ratio helps to reduce the complexity of the dynamic equations significantly because only the speed of the primary motor located in the outermost frame will be needed. Second, because there are studies that show that the chosen ratio seems to produce the best results for Lab simulations [3].

The global position described in (9) is differentiated twice with respect to time. The mean non-gravitational acceleration given by (10) is calculated similarly as the gravitational acceleration in (7)

$$A_{global}(t) = \sqrt{\left(A_{X_{global}}(t)\right)^2 + \left(A_{Y_{global}}(t)\right)^2 + \left(A_{Z_{global}}(t)\right)^2} \quad (10)$$

In the next Section, equations (7) and (10) will be computed to obtain results.

V. Microgravity Determination

Now, we want to compute the amount of microgravity produced by our clinostat there are three factors to be considered. The first factor is the simulation time. We choose a simulation time of 5 min or 300 s, which is a very small amount of time compared with other studies that normally last several hours. The main purpose of selecting 5 min is to reduce the heavy computational load. In Fig. 2, we can observe in blue the gravity vector distribution in frame 3. We can see that the gravity vector in blue has almost covered the entire sphere. The second factor is the speed of rotation. In order to make a comparison with other studies, we select a speed of the 60 °/s or 10 rpm for the outermost frame, or frame 0 (see Fig. 1).

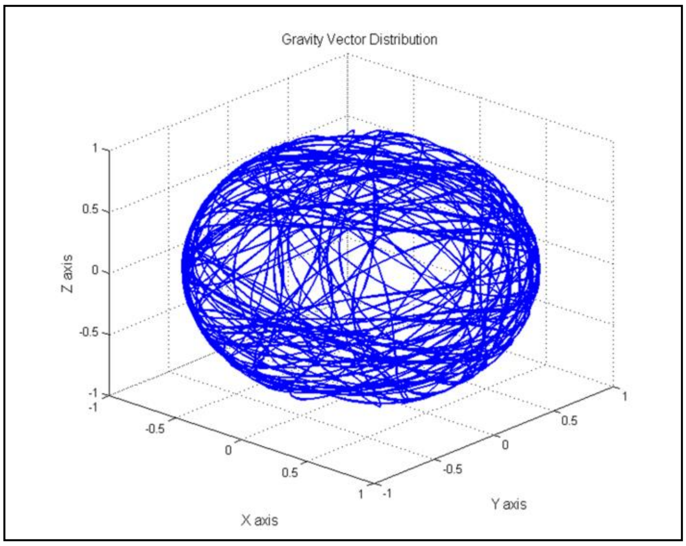

Fig. 2. Distribution pattern of gravity vector (5 min, 10 rpm, 4:1.8 ratio).

The third factor is the ratio of speed. Remember that this ratio was set to 4:1.8 for reasons explained in section IV. In Fig. 3, the mean gravity over time is plotted for a simulation time of 5 min at 10 rpm in the primary motor having a ratio of 4:1.8. Such a mean gravity over time is the gravitational acceleration component of the total acceleration experienced by a sample.

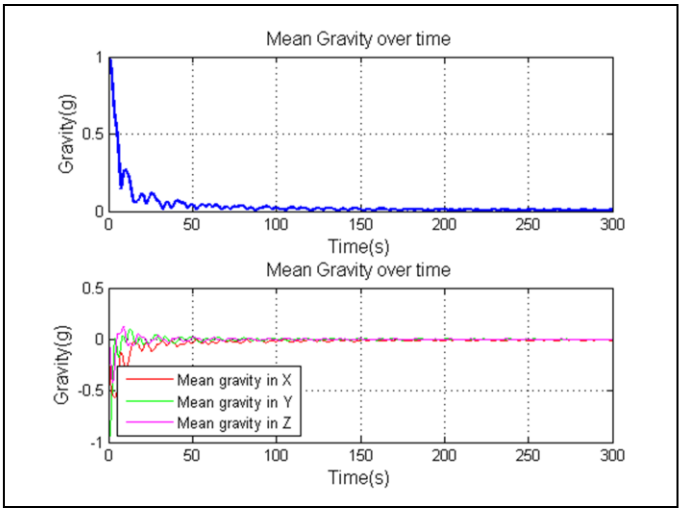

Fig. 3. Mean gravity over time (5 min, 10 rpm, 4:1.8 ratio)

The average gravitational acceleration value obtained for this simulation is $6\text{x}10^{-3}$ g. Although it is six times the expected result, consider that this value was obtained averaging the values of mean gravity over time from sec 200 to 300 for a 5 min simulation.

In Fig. 4, we can clearly see that for the 10 min, 10 rpm, 4:1.8 ratio conditions, the mean microgravity is around $3\text{x}10^{-3}$g and does not go above $6\text{x}10^{-3}$g. In fact, it has a tendency to decrease even more. In order to have a reference for 5 min simulations, we are going to keep our previous value: $6\text{x}10^{-3}$ g.

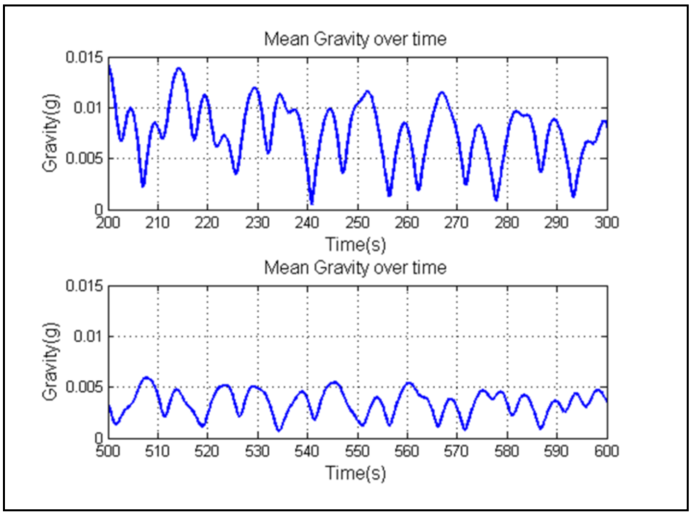

Fig. 4. Mean gravity over time comparison (10 rpm, 4:1.8 ratio).

The second component is calculated giving values to $\vec{r}_3$ and replacing them in (10) in order to find the non-gravitational acceleration in this point. Note in (8) that $\vec{r}_3$ has three components. Therefore, we have to choose each component of $\vec{r}_3$ so that they correspond to a point of a sphere of radius r.

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We defined in Section IV that an acceptable radius r was 10 cm. Thus, we need to find the X, Y, and Z coordinates of a sphere of 10 cm radius. Since all the simulation is running in Matlab, the software has a useful function called sphere (n), where $(n+1)^2$ gives the total number of equally separated coordinates of a sphere. We choose n to be 15, thus there will be a total of 256 coordinates, originating 256 simulations of 5 min each in order to find the non-gravitational accelerations of these 256 points in the sphere.

In Fig. 5, we can observe the histogram of the non-gravitational acceleration for a 10 cm sphere radius.

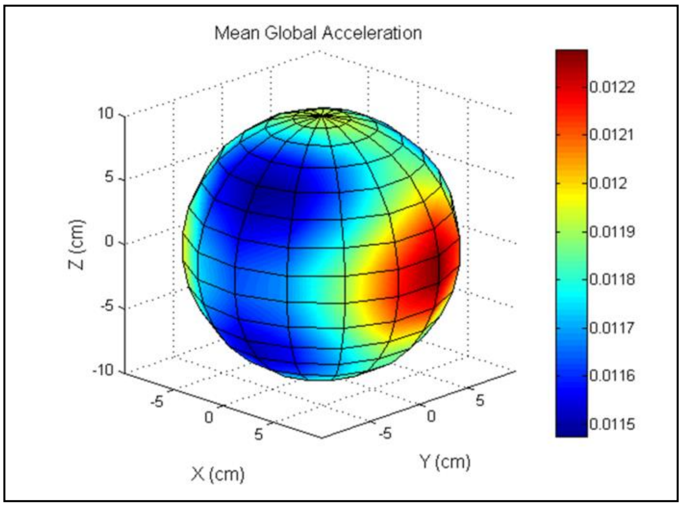

Fig. 5. Histogram of non-gravitational acceleration in a sphere of 10 cm radius, also called mean global acceleration in g units).

The average non-gravitational acceleration obtained at 10 cm is $11.8\text{x}10^{-3}$g. Therefore, the total microgravity experienced by a sample at 10 cm from the center of rotation, obtained in a 5 min simulation is $6\text{x}10^{-3}\text{g} + 11.8\text{x}10^{-3}\text{g} = 17.8\text{x}10^{-3}\text{g}$

VI. Conclusions and Future Work

The first objective of this paper was to obtain microgravity of the order of 10^{-3} g. In the last section we obtained the two components of the total microgravity experienced by a sample. We can see that the non-gravitational component is nearly twice the component generated by gravity. This is because the non-gravitational result strictly depends on the rotational speed and the distance from the center of rotation at which the sample is located [4]. Therefore, we can deduce that there is an improvement in microgravity in terms of omnilateral distribution of the gravity vector as a result of adding an additional DOF. The total microgravity experienced by a sample at 10 cm from the center of rotation, at 10 rpm, with a ratio of 4:1.8 and after 5 min simulation is $17.8\text{x}10^{-3}$g.

In this work, the gravitational acceleration went below $6\text{x}10^{-3}$g in around 8 min of simulation, while the RPM machine employed in [2] has an around 33% chance to obtain such a value after 5h at the same rotational speed. It is even expected to obtain much better total microgravity as simulation time increases.

In addition, the maximum non-gravitational acceleration in the designed 3DOF clinostat was significantly reduced by around 53.07% in comparison with the maximum values obtained with current RPM machines [2] using the same 10 cm radius. The minimum non-gravitational value in the designed clinostat was almost unchanged, establishing another clear advantage of this novel clinostat. This work uses the ratio of 4:1.8 because such a ratio has generated good performance on biological studies [3].

The results obtained in this work can be tremendously improved. There are still unexplored patterns corresponding to different rotational speeds and ratios to test for different simulation periods, in order to optimize the final results of microgravity. As a future work, we are planning to build and test a 3DOF clinostat to produce around 10^{-6} g. We hope to accomplish this task based on the results of this work

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