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EFFECT OF ADDITIONAL WEIGHT ON HUMAN SQUAT EXERCISE STABILITY: GROUND REACTION FORCES AND CENTERS OF PRESSURE

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ABSTRACT

The main focus of this work is to investigate the effect of weight on the stability of human squat exercise. The squat exercise is a common daily activity. Experiments are conducted using one human subject. A VICON motion analysis system integrated with Force Plates is utilized for these experiments. An experimental protocol is developed and followed. This work analyzes the time series of the normal component of the ground reaction forces and each coordinate of the center of pressure. These time series are used to estimate the Lyapunov Exponents using Rosenstein method. MATLAB software package is used for this investigation. The results of this work are compared with results from literature. Present work gives more information relating the safety of the squat exercise when adding additional weight. One can see that the effect of additional weight on stability depends on its value. In the cases of small and moderate additional weight the stability is the same or increases, while for the largest additional weight the investigated stability decreases.

Keywords: Stability of human squat exercise, Lyapunov exponents, effect of additional mass

1. INTRODUCTION

The study of the stability of human motion has been studied in several ways on the literature. The cycle-to-cycle motion has been seen to have inherent variations in the movement [1]. Different effects have been studied on how the human motion changes due to pathological diseases [1,2], age [3], and what type of applications [4] one can use with the findings. Studies tried to relate instability with the variability of the system [1]. Instability happens where the system is not able to adapt. However, Dingwell et al. [2] reported that there is an optimum variability desired in the human motion, when the body makes adjustments in order to find a stable gait in order to continue motion.

In this sense one can say that variability is necessary to have an optimum movement. It is preferable to see variability as the adaptability of the system [1], and as corrective adjustments which were created to maintain the balance and the ongoing movements of the gait [3]. It is important not to discard that this variability in the movement could be chaotic in nature [3] so further investigation is needed. Variability should not be regarded as instability [5], as variability inherently appears in healthy subjects. All of these points are summarized by Cavanaugh [6].

This work deals with the effects of additional mass on the center of pressure motion of human squat exercise. The additional weights to compare are 10, 20, and 32 kg using a vest [7]. The coordinates of the center of pressure and the normal of the ground reaction forces are acquired using force plates and then analyzed. The purpose of this study is to analyze the stability of the center of pressure and normal ground reaction forces of each leg for the human squat exercise. Stability is directly related to how less divergent the movement is between cycles. As such, the study can give us insight in how safe the squat exercise is performed with different weights.

The sections of this work consist of 1) methodology used for a) data acquisition, b) data filtering, and c) stability analysis, 2) experimental protocol to include d) warm-up procedure, and e) technique and procedure, 3) results, and 4) discussion and conclusions.

2. METHODOLOGY

Data Acquisition: The data acquisition system in the Biomechanics Laboratory at UTRGV consists of 10 Vicon Cameras and 2 AMTI OR6 Series Force Plates shown in Fig.1. The cameras need calibration each time the Vicon system is turned on. The main acquisition tools are the force plates capturing the ground reaction forces of the subject. The software

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Nexus is used to calculate the center of pressure's coordinates after the motion capture.

FIGURE 1: VICON CAMERAS AND FORCE PLATES SETUP

The subject for the trials has a height of 1.70 meters and a mass of 77 kg. The subject positioning on the force plates can be seen in Fig. 2. The origin of the global coordinate system is positioned in the upper-left corner of the force plate of the right foot of the subject. In other words, the origin is the posterior and lateral (with respect to the subject) corner of the plate of the right foot of the subject.

FIGURE 2: MARKERS ON HUMAN SUBJECT

Data Filtering: The double pass Butterworth filter is used [8,9] in this work. The double pass filter eliminates the 90º angle shift. The formulas used are as follows [8,9]

$$\omega = \frac{\tan\frac{\pi f_c}{f_s}}{C},\ K = \sqrt{2}\omega,\ K_2 = \omega^2,\ a_0 = \frac{K_2}{(1+K+K_2)} \quad (1)$$

$$K_3 = \frac{2a_0}{K_2},\ a_1 = 2a_0,\ a_2 = a_0 \quad (2)$$

$$b_1 = -2a_0 + K_3,\ b_2 = 1 - 2a_0 + K_3 \quad (3)$$

First, one calculates the parameter ω, where f_c is the cutoff frequency, f_s is the sampling frequency which is 1000 Hz and C is the correction factor for a double pass filter which is $C = 0.802$ [9]. Subsequently equations (1-3) are used to find the filter coefficients $a_0, a_1, \ldots b_2$. To filter the raw data in the time domain one uses the following formula [8,9]:

$$X^1(nT) = a_0X(nT) + a_1X(nT-T) + a_2X(nT-2T) + b_1X^1(nT-T) + b_2X^1(nT-2T) \quad (4)$$

where X^1 is the filtered data, X unfiltered data, T is the time step size and n represents the n^{th} data point to be filtered [9]. Frequencies from 1 Hz to 15 Hz in 0.1 Hz step-size were considered in order to find the correct cutoff frequency [9]. Furthermore after this we calculate the residuals [9] to find the cutoff frequency:

$$R(fc) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(X_i - \widehat{X}_i)^2} \quad (5)$$

where X_i is the i-th value of the sample, and $\widehat{X}_i$ is the filtered data i-th value of the sample. Cutoff frequencies result as 3 Hz and 3.6 Hz for the ground reaction forces and center of pressure coordinates, respectively. The steps of finding cutoff frequencies are given in Refs. [8] and [9].

Stability Analysis: Stability of a movement has been a focus of investigation for several years. Orbital stability has been used in the past by Hurmuzlu and Basdogan [10] using Floquet multipliers (eigenvalues of the Jacobian Matrix) analyzing the system of equations, and by Dingwell [7]. Present work uses Largest Lyapunov Exponent.

Stability can be measured as the constant of the average exponential rate divergence in a trajectory, Stegiou [1,3] and Dingwell [2,12]. The formal definition can be seen in these references. In essence it measures local perturbation, which is different from orbital stability.

The state space from the time series can be any data obtained experimentally [2]. As such the state space can be defined as:

$$X(t) = [x(t), x(t+T), \ldots. x(t+(d_E-1)T)]$$

where $X(t)$ is the time delayed reconstructed vector with dimension d_E, $x(t)$ is the time series to be reconstructed, T is the time delay [9]. The time delay for the reconstruction can be chosen from the minimum of the minimum of the mutual information function[13]. However, one would want to analyze ranges in order to investigate it. For the embedding dimension one can use the Kenel approach [14]. The embedding dimension of 3 is used since basically it gives convergent results as recommended by Rosenstein [15]. From experiments and having the trajectories one can have [2]:

$$d(t) = d_0 e^{\lambda_1 t} \quad (6)$$

where *d(t)* is the mean separation or divergence which one calculated from the nearest neighbors. As time passes it will grow exponentially. For this exponential divergence, one needs to define the following distance [15]:

$$d_j(i) = \min_{X_k} \| X_j - X_k \| \quad (7)$$

Equation (7) gives the minimum distance from point X_j, called $d_j(i)$ at time i. The absolute value of the difference between j and k needs to be greater than the mean period. In order to estimate the Lyapunov exponent one obtains the slope of the regression line of the averages across j of $d_j(i)$ for each time i. One calculates

$$y(i) = \frac{1}{\Delta t} \langle \ln d_j(i) \rangle \quad (8)$$

where $\langle \cdot \rangle$ denotes the averages across all j. One can see an example of the calculations of the curve you generate. In this point we estimate the Lyapunov exponent as the slope of the approximately linear part of start of the curve $y(i)$. As an example of this we can be seen in Fig. 3.

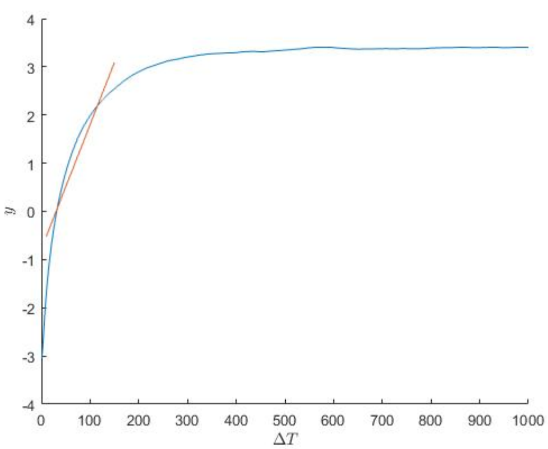

FIGURE 3: ESTIMATING THE LYAPUNOV EXPONENT WITH THE LEAST REGRESSION LINE OF THE CURVE

Is important to mention that another method that is used is Wolf's [16] algorithm. Here the difference is that Wolf's method follows a point on the reconstructed state space and estimates the Lyapunov Exponent as the two points diverge from each other. However the recommendation is to use Rosenstein as stated by Dingwell with data that is inherently come from noisy data[17]. Wolf's method will be used for comparison.

3. EXPERIMENTAL PROTOCOL

Warm-up procedure: The subject warms up [8,15], performing squats for 5 minutes and resting for 3 minutes before the trials begin**.**

Exercise technique and procedure: Squat exercises are performed. The origin of the global coordinate system is in the corner of one of the force plates, as explained before. The foot during the exercise is fixed and marked [8]. The *x*-axis is on posterior-anterior direction. The anterior direction is the positive direction. The *y*-axis is the lateral-medial direction of the right foot. A block was positioned so the subject can maintain a regular squat exercise depth at all times. Also, the subject arms are kept anteriorly at all times, Fig. 4.

The experiment consisted of 4 trials with 5 minutes rest in between with various weights. The first trial, the subject was using his own bodyweight. In the second trial, the subject was using a backpack with 10.16 kg of added weight. In the third and fourth trials, the subject was using a vest with backpack with added weight of 20.69 kg and 32 kg, respectively [8].

4. RESULTS

The center of pressure of the right leg with no additional mass ranged in the *x*-axis from 100 mm to 160 mm and in the *y*-axis from 185 mm to 210 mm. The center of pressure in the left leg with no additional mass ranged on the *x*-axis from 80 mm to 180 mm, and in the *y*-axis from 620 mm to 655 mm. Figures 5-10 show comparisons between no additional mass and additional mass cases.

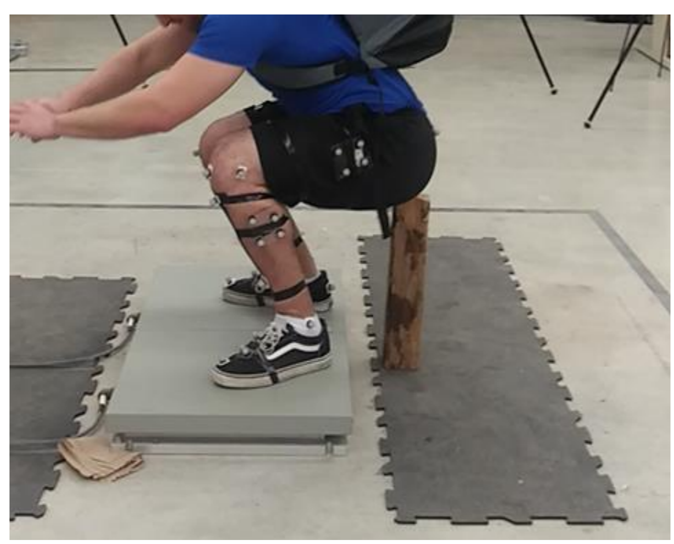

FIGURE 4: SUBJECT SQUAT CONFIGURATION

With 10 kg of additional mass in the right leg, the range of movement of the Center of Pressure (COP) on the *x*-axis ranged from 100 mm to 180 mm, and in the *y*-axis from 185 mm to 225 mm, Fig.5. There is more variation on the edges. However, one can see that it ranged more between 100 mm to 160 mm on the *x*-axis, and between 195 mm to 220 mm on the *y*-axis. Similar ranges are seen for the left leg, with and without additional 10 kg, Fig. 6. One can notice that COP ranged more between 100 mm to 160 mm on the x-axis, and between 635 mm to 650 mm on the *y*-axis.

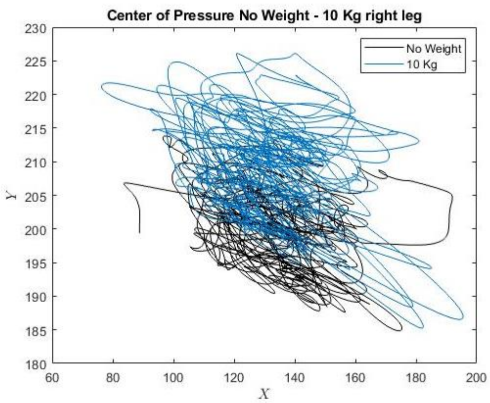

FIGURE 5: POSITION IN MILLIMETERS OF THE CENTER OF PRESSURE IN THE RIGHT LEG WITH NO WEIGHT AND 10 KG OF ADDED MASS.

For 20 kg of additional mass, in the case of the right leg, the range of motion of COP ranges from 100 mm to 180 mm on *x*-axis, and from 205 mm to 220 mm on *y*-axis, Fig. 7. For the left leg Fig. 8, one can see that the motion of COP in the case of 20 kg of additional weight is contained in the same range as the case of no additional weight. The COP is oscillating less with additional weight.

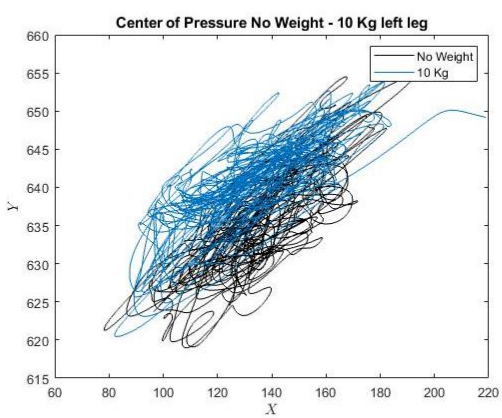

FIGURE 6: POSITION IN MILLIMETERS OF THE CENTER OF PRESSURE IN THE LEFT LEG WITH NO WEIGHT AND 10 KG OF ADDED MASS.

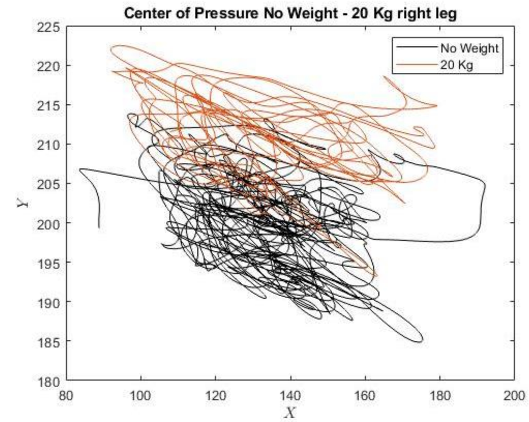

FIGURE 7: POSITION IN MILLIMETERS OF THE CENTER OF PRESSURE IN THE RIGHT LEG WITH NO WEIGHT AND 20 KG OF ADDED MASS

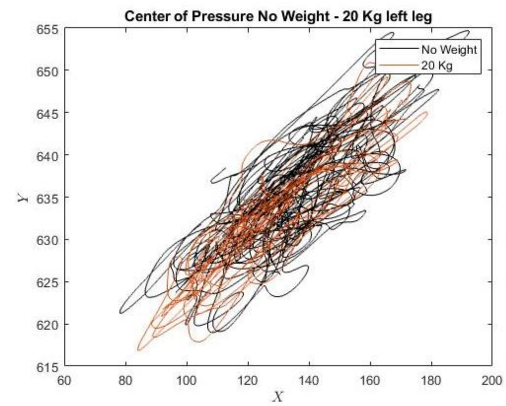

FIGURE 8: POSITION IN MILLIMETERS OF THE CENTER OF PRESSURE IN THE LEFT LEG WITH NO WEIGHT AND 20 KG OF ADDED MASS.

With the highest value of added weight, 32 kg, one can see that the COP ranged from 100 mm to 180 mm on *x*-axis, and from 205 mm to 220 mm on y-axis, Fig. 9. For the left leg the COP ranged from 80 mm to 180 mm on *x*-axis, and from 625 mm to 660 mm on y-axis, Fig. 10. One can see that COP ranged more between 100 mm to 150 mm on *x*-axis, and between 630 mm to 650 mm on the *y*-axis.

Rosenstein method [15] is used in this work, instead of Wolf's [16] method, in order to calculate the Lyapunov Exponents, as recommended by Dingwell [17]. First, the Lyapunov exponents are calculated with different time delays and orbital times to analyze how different the Lyapunov exponents are for the right leg ground reaction forces with no weight. One can see in Fig. 11 that there is no significant difference with the orbit time and with the time delay. A comparison is made in Fig. 12. This range of values with Wolf's algorithm as we vary the evolution time (the amount of time between Lyapunov exponent calculations in the method) we see that the values between the two methods are around the same scale. In order to proceed with the analysis we will use the

Rosenstein's method. Dingwell [17] stated that is best used in order to get a constant Lyapunov Exponent and also because the method is not affected but noisy behavior.

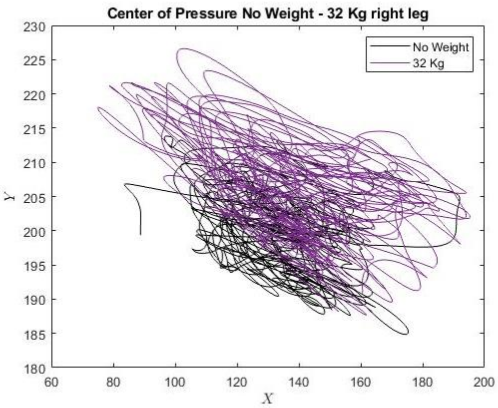

FIGURE 9: POSITION IN MILLIMETERS OF MEDIAL-LATERAL COORDINATE OF TIBIAL CENTER OF MASS DURING SQUATTING WITH NO ADDITIONAL WEIGHT, AND ADDITIONAL WEIGHT OF 10 KG.

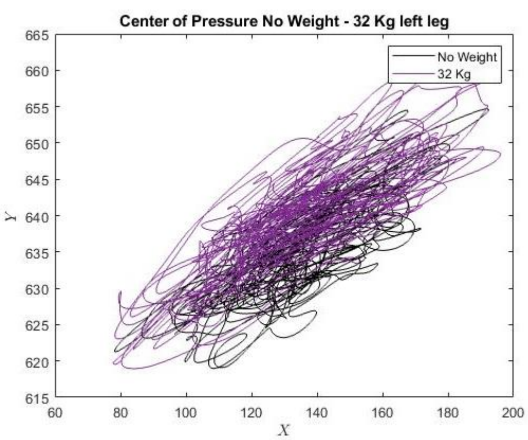

FIGURE 10: POSITION IN MILLIMETERS OF THE CENTER OF PRESSURE IN THE LEFT LEG WITH NO WEIGHT AND 32 KG OF ADDED MASS.

Look et al. [18] reported values which were on this scale. Tenbroek [19] also made comparison of the methods in which Rosenstein method will yield a higher value in the same scale, sometimes as high as double the estimation. Present work uses a time delay of 3 for all weights, and one can see the results in Fig. 13.

5. DISCUSSION AND CONCLUSIONS

This research deals with the effect of additional weight on the stability of the center of pressure and ground reaction forces on the squat exercise. As one adds weight, there is a gain in stability, except in the case of 32 kg of added weight. This effect can be seen overall in Figs 14 and 15. In Fig. 13 the stability of the ground reaction force for the right leg is more stable than the left leg.

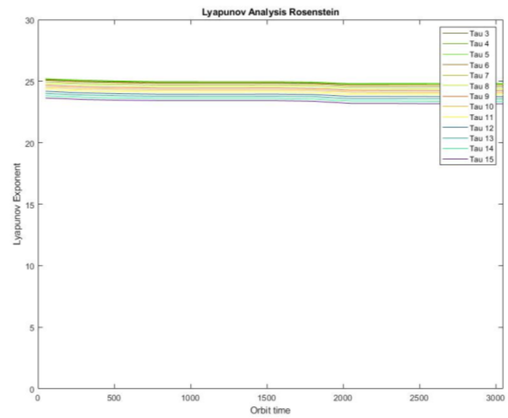

FIGURE 11: LYAPUNOV EXPONENT CURVES WITH ROSENSTEIN METHOD WITH DIFFERENT TIME DELAY RECONSTRUCTION FOR THE GROUND REACTION FORCES WITH NO WEIGHT.

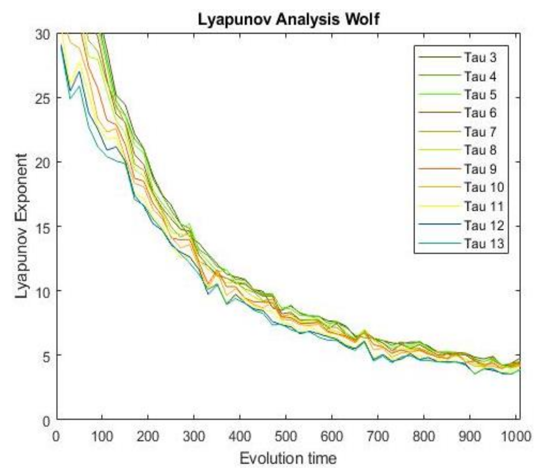

FIGURE 12: LYAPUNOV EXPONENT CURVES WITH WOLF'S METHOD WITH DIFFERENT TIME DELAY RECONSTRUCTION FOR THE GROUND REACTION FORCES WITH NO WEIGHT.

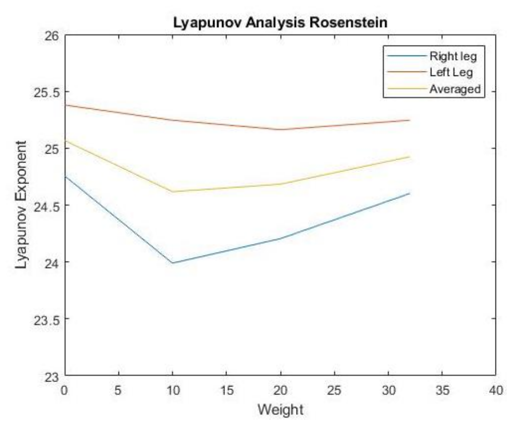

FIGURE 13: LYAPUNOV EXPONENT CURVES WITH ROSENSTEIN METHOD WITH DIFFERENT WEIGHTS FOR THE GROUND REACTION FORCE.

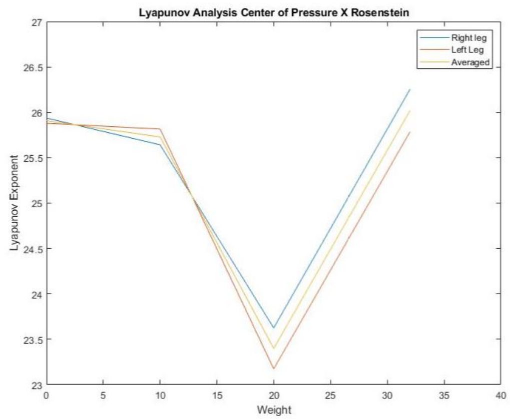

FIGURE 14: LYAPUNOV EXPONENT CURVES WITH ROSENSTEIN METHOD WITH DIFFERENT WEIGHTS FOR THE CENTER OF PRESSURE'S X COORDINATE

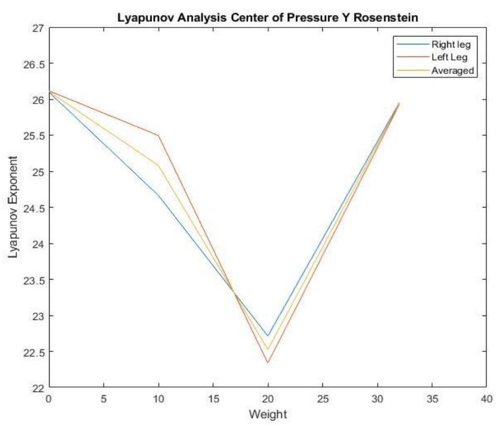

FIGURE 15: LYAPUNOV EXPONENT CURVES WITH ROSENSTEIN METHOD WITH DIFFERENT WEIGHTS FOR THE CENTER OF PRESSURE'S Y COORDINATE

Moreover, one can see that the ranges of movement of COP of both legs increase as one adds weight, for both 10 and 32 kg. There range of movement in the center of pressure for added weight 10 and 20 kg as seen in Figs. 5 – 8.

This is in agreement with the Lyapunov Exponents that correspond to lower values, in particular for COP on both *x* and *y* directions for 20 kg. Stability analysis with Lyapunov Exponents has given insight that the Ground Reaction Forces gain stability for 10 and 20 kg. This correlates with the low range of movement of COP of the legs having a common range of movement in most of the orbits.

There is the conjecture now, that there is also a range of additional weight for which the human subject has a better control of the movement, as such COP stabilizes more with 20 kg additional weight. However, both additional weights, 10 and 32 kg, show larger Lyapunov Exponents for COP coordinates, Figs. 14 and 15, so lower stability of the squat exercise is predicted. The use of one subject is a limitation of the current investigation. One can mention that in similar studies [20-22] the number of subjects ranged from 6 to 30. Although the subject is not overweight, the obesity is simulated with additional weight [23-25]. Future work will try to study the ranges where stability is obtained and the threshold where it unstable again, make a random selection from a group of volunteers in order to minimize the variability in male and female subjects, athletic to non-athletic subjects and left a right brain persons in order to generalize the results.

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