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(Research Article)

# Stability Analysis of Muscular and Skeletal System of Human's leg segments (Thigh and Shank)

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**Abstract**

Muscular and Skeleton systems are the key elements for strength, support and locomotion of human system. Shank, a part of the human leg, not only supports body weight but provide locomotion at the time of walking and running. This part may be considered as an assembly of several mechanical springs, mass and damping elements. The mode of vibration and stability will depend upon the spring stiffness, damping coefficient and their arrangements in muscular and skeletal system. The modeling and analysis of this system has assumed that there are four stages of growth to tackle stability. The first stage (0-1 years) is formation stage where the bone forms from the cartilage to gain stiffness and damping. The second stage (1-20 years) when the system is getting stabilized and considered more stable, because of balance between stiffness and damping of the muscles and bone. The value for damping starts decreasing in the third stage (20 to 65 years) leaving stiffness alone to stand the locomotion at later years. The fourth stage (65 to 90 + years) relates to old age, in which both the damping coefficient and stiffness start deteriorating, causing considerable instability. The stability analysis is carried out with the mean values taken in these four stages to show how the system changed from one stage to another. A linear model is considered for simple analysis that shows that stiffness rate increases and damping decreases with the increasing age. This often takes place after the second stage. The Simulation Program with integrated Circuit Simulation Program with Integrated Circuit Examples (SPICE) is used for discussion of these results.

*Keywords:* Muscular and Skeletal System of Human, Vibration, Damping, stability of a Leg, Knee Joint.

## 1. Introduction

The muscular and skeletal system are critical for support, locomotion, protection of internal organs, production of blood cells, storage and release of mineral and fats that is essential for good health and shape maintenance for human system. The system was studied since the beginning of the development of biomechanics dating back to about 1450A.D. [1]. Human skeletal system is composed of bones and cartilage commonly known as endoskeleton. Skeletal muscles, ligament, tendon and other connective tissues are on the outside of this endoskeleton. Bones support muscles and transmit the forces produced when muscles contract. From mechanical point of view bone joints acts as fulcrum and support points for body motion.

Ageing brings major changes in body composition. It affects the functional status in older people that includes progressive decrease in muscle mass, strength, and quality accompanied by an increase in fat mass [2,3]. Changes in skeletal muscles are critical for stability and locomotion, because of loss of muscle mass [4] known as sarcopenia. All these accompanied by changes in body chemistry not only affects the muscular skeletal deterioration but also affect negatively on quality of life and functional status in older adults. All these leads to fast ageing, decrease in body immune contributing to several diseases like Osteoarthritis, Rheumatism, Diabetics, hypertension etc.

In this paper, attention is focused on modelling and stability of a leg as a function of age. Leg is very important part of the lower limb body consist of the thigh with largest single bone as femur and part of the leg below knee joint having patella ligament as shown in the Figure 1 [5,6]. It has the longest bone of the body between thigh and knee joint. The leg from the knee to the ankle is called crus or cnemis. The calf is the back part of the bone and the tibia make up the front of the bone. Cartilage has almost no blood vessels and is very bad at repairing itself. Bone is full of blood vessels and is very good for self-repair. It is high water content that makes cartilage flexible.is like a rubbery meniscus cartilage

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absorbs shocks and side forces like bearings. The knee joint supports the translation and rotation of the muscles and joints are modeled using basic mechanical elements such as spring, mass and damper. These components can be arranged in series or in parallel depending upon the behavior of skeletal-muscular system. There has been numerous studies to model and investigate mechanical propertitis of human leg and muscular joints [7-9].However, there is not enough work done using vibrational components to model the behavior of ageing effect on stability and related factors. Using equivalency of electrical system and their impedance arrangement and approach an effort is made to solve the problem of ageing effect in human behavior.

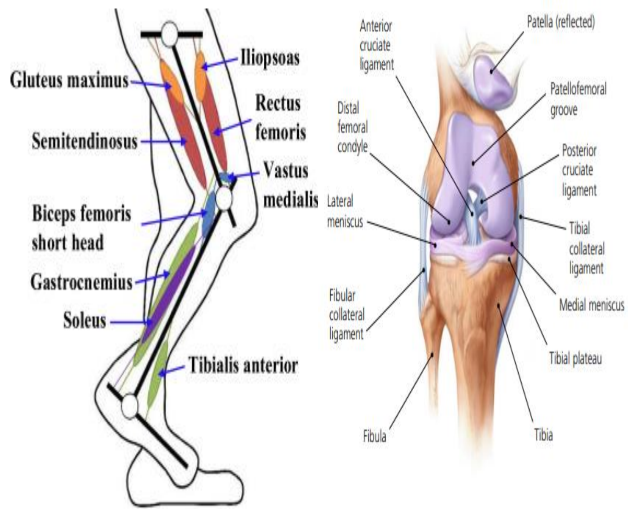


**Figure 1.** Thigh and leg that supports the body weight and their structure

The development for locomotion and movement stability in to four stages of human use: toddlers, adolescent, mature adult and elderly. The change in the stiffness and damping properties of the system are discussed stage by stage. These change of the mechanical and of the systems is shown using the simplified mathematical equations based on spring, mass and damping related physical properties.

In addition, equations are used to find the best feedback to stabilize the system. The pro and cons of the ideas proposed in the paper. The SPICE (Simulation Program with Integrated Circuit Examples) simulations of the system are used in the electrical engineering department at this University [10], for system study using familiar simple linear differential equations.

## 2. Modelling of Leg

Every motion of human leg involves combination of translation and rotational motion. An ideal model of leg is developed with the assumption that the joints operate in the rotational mode, while the muscles and bones only generate translational motion. Figure 2, shows the assumed structure of leg, in which the rotational motion occurs about Y axes, Translational motion occurs only at $T_1$ and $T_2$ and rotational motion happens at knee joint, $R_1$ and $R_2$.

The following assumptions are made to have the mathematical modeling the human leg:

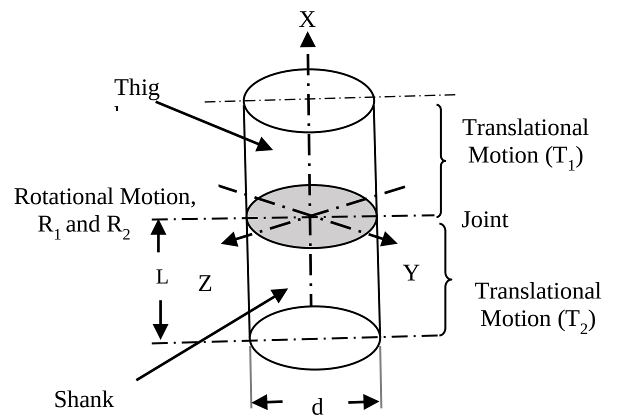


**Figure 2.** Simulated structure of leg showing XYZ axis at the joint

1. The upper part of the body supported on legs is considered rigid and simple geometrical shape of cylinder for both thigh and shank with uniform density.
2. The weight of the foot below the ankle is neglected.
3. The stiffness property of the system is assumed constant and modeled to be a linear spring.
4. The damping property of the skeletal system forming the leg is assumed constant.
5. Skeletal structures within a segment are modeled as a single rigid body with the geometry of a cylinder length (L), diameter (d), and mass (m).
6. The moment of inertia about each skeletal mass and each soft tissue mass in the plane of motion is approximated from the length (L) and diameter (d) of each cylinder.
7. Relative motion between the joint and the skeletal mass of each segment has four degrees of freedom, two translational and two rotational.
8. The system starting (initial) position is in the standing position.
9. The model is restricted to the walking movement with angles between $0^o$ and $60^o$.
10. A simple mathematical model is developed based on the above assumptions. Real translational system ($T_1$ and $T_2$) is equivalent to system shown in Figure 3, and can be represented in the form of a simple general differential equation of single degree of freedom representing vibration equation

$$m\ddot{x} + c\dot{x} + kx = f(t) \tag{1}$$

Where, m is the mass of the system, k is the stiffness property of the system, c is the damping property of the system, \x, $\dot{x}$, and $\ddot{x}$ is the linear displacement, velocity and acceleration of the system.

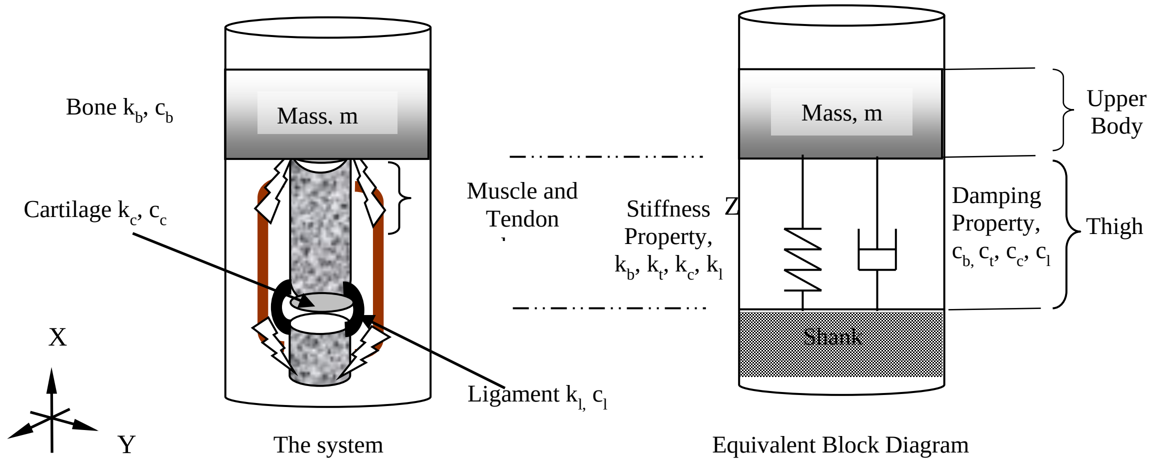


**Figure 3.** Mathematical modelling of real translational system $T_1$

The translational motion $T_1$ and $T_2$, for Fig.2 is written as

$$m\ddot{x} + c\dot{x} + kx = f_1(t) \tag{2}$$

$$m\ddot{x} + c\dot{x} + kx = f_2(t) \tag{3}$$

$T_1$ and $T_2$ is make up of a multiple degree of freedom (MDOF) system, which is nothing more than the sum of sets f single degree of freedom (SDOF) systems. So, the translation motion of the system is written as,

$$M\ddot{x} + C\dot{x} + Kx = F(t) \tag{4}$$

M is the sum of $m_1$ and $m_2$, C is the sum of $c_1$ and $c_2$, K is the sum of $k_1$ and $k_2$, and F(t) is the sum of $f_1(t)$ and $f_2(t)$.

Besides the translational movement, rotational movement is also involved at the joint. It is assumed that here are two rotation movements about the z-axes, $R_1$ and $R_2$, for the system. Each can be equated into a basic equation, that of a SDOF in Figure 4.

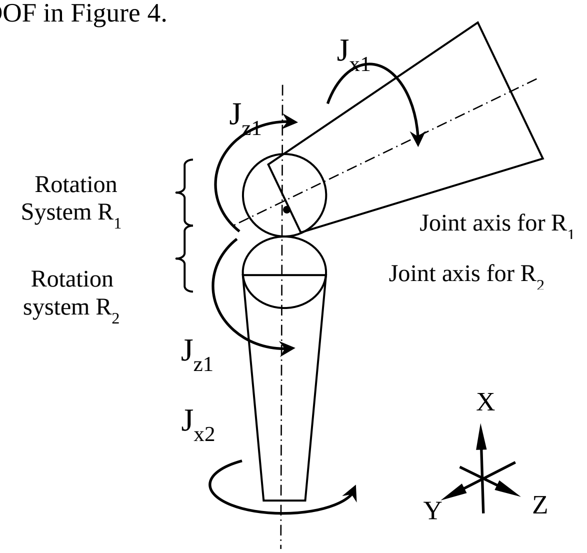


**Figure 4.** The rotation system about the joint axes as $R_1$ and $R_2$

$$J\ddot{v} + b\dot{v} + sv + rf_b = \tau(t) \tag{5}$$

Where, J is the polar moment of inertia, $v$, $\ddot{v}$, and $\dot{v}$ is the angular displacement, acceleration and velocity; b is the stiffness property, and s is the damping property of the system. $\tau$ (t) the sum of $T_1(t)$ and $T_2(t)$; the contact force, "$f_b$", is where the bones mesh, and r is the proportionality constant.

Figure 3, shows that polar moment of inertia (J) and its direction by the movement at the knee joint of the two leg segments. The leg is modeled as a cylinder, which moves around the z-axis. The leg of a male with a total body mass of 80 kg and height of 1.80 m has segment mass of lower leg, m, of 4.88 kg and the distance from the joint axis to the segment center of mass to be 0.246 m. Radius of the quadriceps muscle with respect to a joint center, rf = 0.033 m [1]. rf is equal to 8% of the length, l = 0.41 m, of the thigh.

The Polar moment of inertia (Jo) is defined as the summation of inertia moment around x axis ($I_x$) and z axis ($I_z$) with y axis as constant,

$$J_0 = I_X + I_Z \tag{6}$$

In this case, $I_x$ is negligible since the change of angle around x-axis is very small. Hence, $J_o = I_z$ Calculating moment of inertia about z-axis for a cylinder as shown in Figure 4, with k is a constant.

$$I_z = k\,\frac{m\left(3rF2 + 2l\right)}{12} \tag{7}$$

The moments of inertia of each component are computed from Figure 5, using the parallel-axis theorem. In the calculation, the moment of inertia of the hemispheres are omitted because the mass of these two rigid body is inconsiderable as compared to thigh and shank and is considered almost equals to zero.

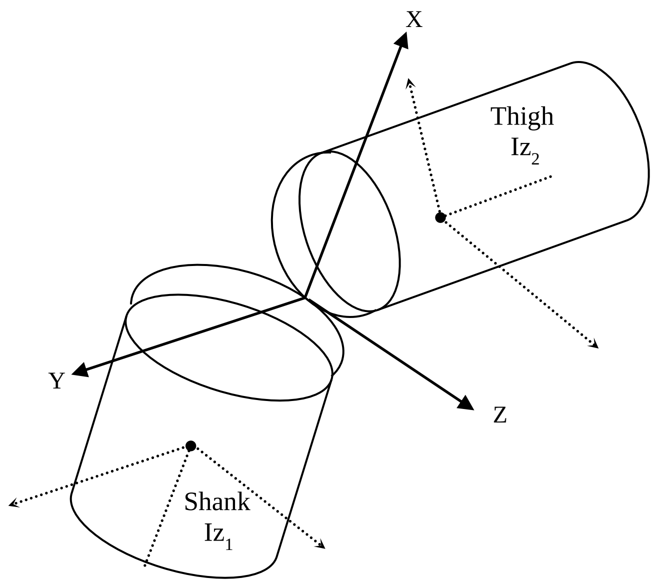


**Figure 5.** Moment of Inertia of shank and thigh about Knee joint axis

Cylinder I (Shank)

$$Iz_1 = k\frac{m\left(3rF2 + l2\right)}{12} + mx'^2 \tag{8}$$

$$Iz_1 = \left(38.526k + 1.544\right)10^{-3} \tag{9}$$

Cylinder II (Thigh)

$$Iz_2 = k\frac{m\left(3rF2 + l2\right)}{12} + mx'^2 \tag{10}$$

$$Iz_2 = \left(44.029k + 1.764\right)10^{-3} \tag{11}$$

Combining with whole body is written as

$$Iz = Iz_1 + Iz_2 \tag{12}$$

$$Iz = \left(82.55k + 3.308\right)10^{-3} \tag{13}$$

Damping and stiffness are the physical properties of the bone (b), cartilage (c), ligament (l), tendon (t) and other connective tissues in the rotational system. Again, the rotational damping (*b*) and that of stiffness (*s*) property of each element are summed together

$$\frac{1}{s} = \frac{1}{s_1} + \frac{1}{s_t} + \frac{1}{s_c + s_b} \tag{14}$$

$$\frac{1}{b} = \frac{1}{b_1} + \frac{1}{b_t} + \frac{1}{b_c + b_b} \tag{15}$$

The rotation motion for $R_1$ and $R_2$ is written as:

$$J_1\ddot{v}_1 + b_1\dot{v}_1 + s_1v_1 + r_1 f_{b1} = \tau_1(t) \tag{16}$$

$$J_2\ddot{v}_2 + b_2\dot{v}_2 + s_2v_2 + r_2 f_{b2} = \tau_2(t) \tag{17}$$

The ratio between $r_1$ and $r_2$,

$$\frac{r_1}{r_2} = N \tag{18}$$

With the assumption that the ratio of $r_1$ with respect to $r_2$, is equal to 1, then

$$v_1 = v_2 \qquad \dot{v}_1 = \dot{v}_2 \qquad \ddot{v}_1 = \ddot{v}_2$$

Finally, $R_1$ and $R_2$ make up a MDOF system, which could be written as,

$$J\ddot{v} + b\dot{v} + sv = \tau(t) \tag{19}$$

In order to combine the rotation and translation systems together, the translational displacement (*x*) and angular displacement (ν) is related by $\ddot{x} = 1 - \cos\ddot{v}$
The final equation of motion is written as

$$M_{System}\ddot{x} + C_{System}\dot{x} + K_{System}x = F(t)_{System} \tag{20}$$

Where, $C_{System}$, $F(t)_{System}$, $K_{ystem}$, and $M_{ystem}$ are the effective damping, force, stiffness and mass of the system.

## 3. Results and Discussion

Results were obtained using a Simulation Program with Integrated Circuits Emphasis, PSPICE, is used in the simulation of the transient reaction of the muscular and skeletal system. PSPICE could be used in the simulation of a system differential equation using an analog computer-type approach.

A library of basic system elements, SYS.LIB, which has been developed by Mr. Joel B. Brown and Dr. Charles E. Smith from the University of Mississippi, [10] is used. The written program is then run on MicroSim Pspice A/D Evaluation version 8.0 program to simulate the output x(t) as shown in Fig. 6. Where Msystem is the inverse of MUL1; stiffness of the system, Ksystem is the multiplication of MUL2, MUL3 and 10, and damping of the system, Csystem is the multiplication of MUL2, MUL3 and 10. The variables, $M_{system}$, $C_{system}$, and $K_{system}$ are the values according to the age group as shown in Table 1, and F(t)system was set to 1.

**Table 1.** Estimated value for damping and stiffness property of different age groups

| Age group ⇓⇓ | $M_{system}$ ⇓⇓ | $C_{system}$ ⇓⇓ | | | | $K_{system}$ ⇓⇓ | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | K= C | K< C | K >C | | K= C | K< C | K >C |
| 0 – 1 | 3.61 | Low | 0.001 | 0.1 | 0.001 | Low | 0.001 | 0.001 | 0.1 |
| 1 – 20 | 20.3 | | 1 | 1 | 0.1 | | 1 | 0.1 | 1 |
| 20 – 60 | 30.0 | | 10 | 10 | 1 | | 10 | 1 | 10 |
| 60 – 90 | 32.8 | High | 100 | 100 | 10 | High | 100 | 10 | 100 |

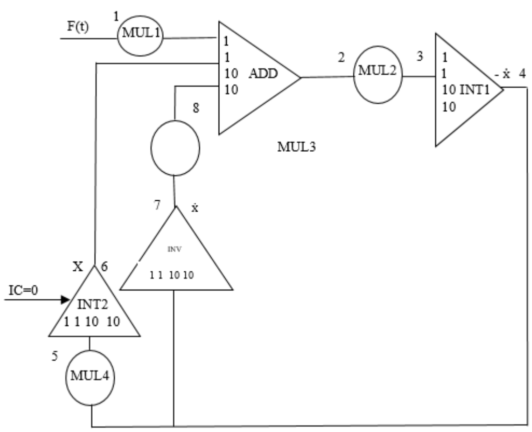


**Figure 6.** Analysis using PSPICE Program

The obtained results have supported the argument that human's leg could be categories into the three basic system of underdamping, critically damping and overdamping.

Figure 7 shows the response of the age group from 0 to 1 year for three conditions (C = K, C < K, and C > K) of locomotive systems. However, biological tests have proven that babies less than a year old have very soft bones [11] making the damping factor in their legs greater than its related stiffness factor. Thus, the graph of C > K should be used in the study. This goes hand in hand with the result obtained from the C > K where with a constant applied force to the system, the system behaves in an unstable (oscillatory manner as we would expect in a baby. The unstable system of a higher damping factor causes the human at this age to be rapid in movement but unable to support its body mass till the bone and cartilage stiffen

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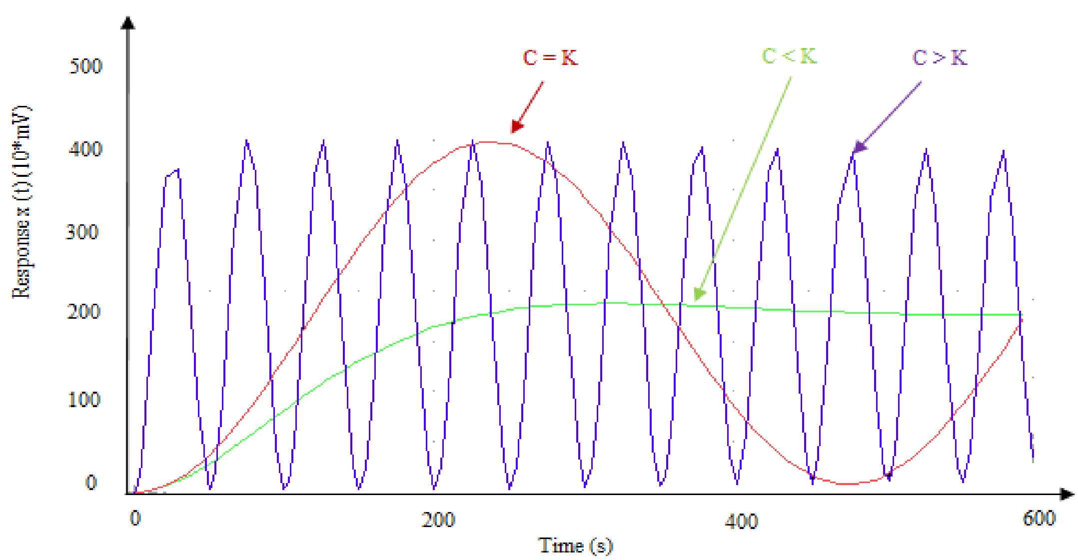


**Figure 7.** Response x(t) of the Age Group 0 to 1 Years with $M_{system}$ = 5.67 kg

Figure 8 reports the response of the age group 1 to 20 years. However, since it was shown that at 1 years of age, the damping is larger than the stiffness, this leads to the conclusion that the valid results are that of the C > K case and possibly the C = K case. The oscillation associated with the result is minimal compared to that of the oscillation result from the 0 to 1 year case. This seems to be the most stable case when the human has already learned to walk and soon learns to run and sprint. The oscillation is shown to decay quickly in the critical damping (C = K) which we would expect a human to achieve during his or her optimum performance age (about 20 years of age).

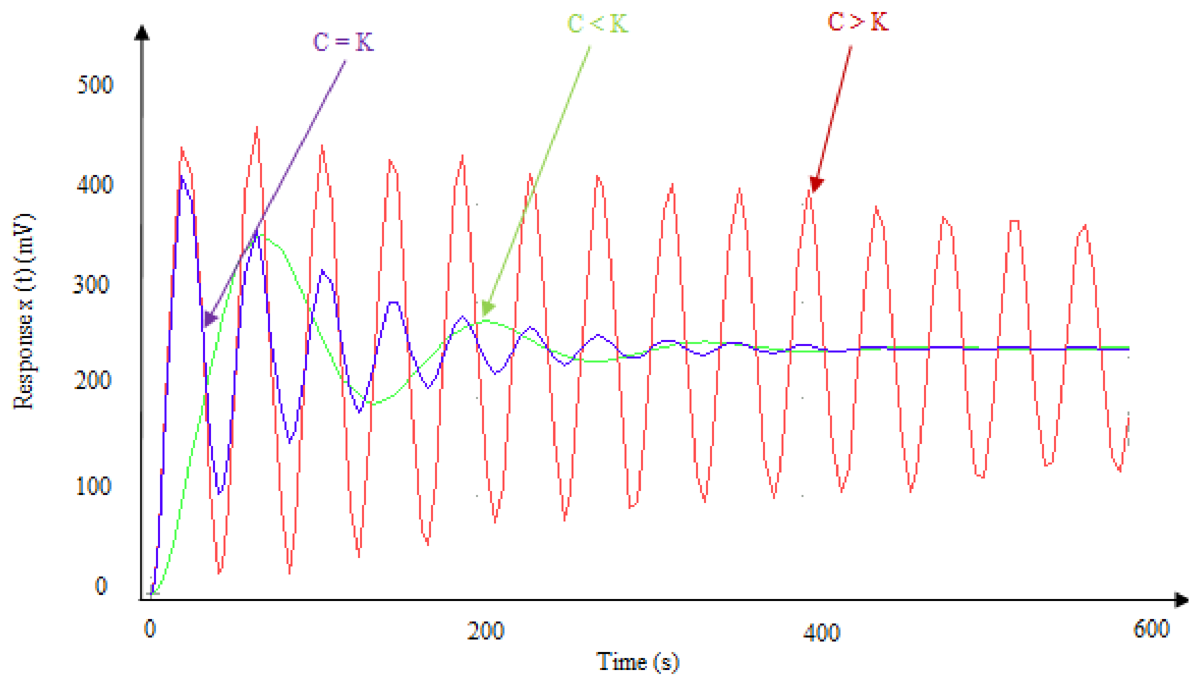


**Figure.8.** Response x(t) of the Age Group (1 year to 20 years) with Msystem = 39.65 kg

For the age group of 20 years to 65 years, with obesity on setting in, instability of the leg movement increases relative to the amount of body mass accumulated with respect to the muscle growth. As shown in Figure 9, the critically damped case is used as the body is already assumed to be in 'harmony' having developed proper damping and stiffness systems. The condition (C = K) graph shows a higher instability when a constant force is applied to the system when compared to that of 1 year to 18 years old (C = K) .

case. The amount of displacement in this system is greater than that of the case in the 1 to 20 years' case leading to a higher instability. The criticality damped graph is seen to decay rapidly, bringing the system accustomed to the added force. It is at this time that the bones have stopped growing and age is setting in at the later years where the bones start to become more brittle. With this, it is easy to expect that obese people in their later years find great difficulty in walking followed by several diseases, let alone running

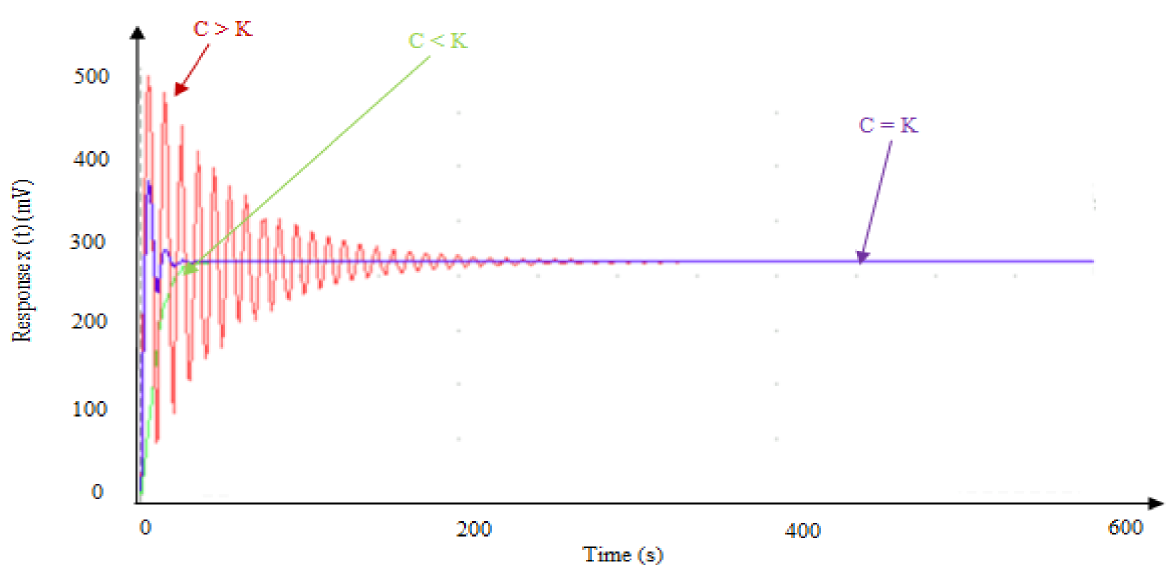


**Figure 9.** Response x(t) of the Age Group (20 to 65 years) with Msystem = 23.45 kg

During the age group of 65 to 90 years, and beyond, both damping and stiffness factors are increased, but weight levels are assumed to reduce from lower metabolic lifestyles. It is evident from the Figure 10, that stability is greater in that case, with assumed critical damping, compared to that of the higher oscillations found in the age group of 20 years 65 years. However, this amount of displacement is very dangerous with brittle bones setting in at this age.

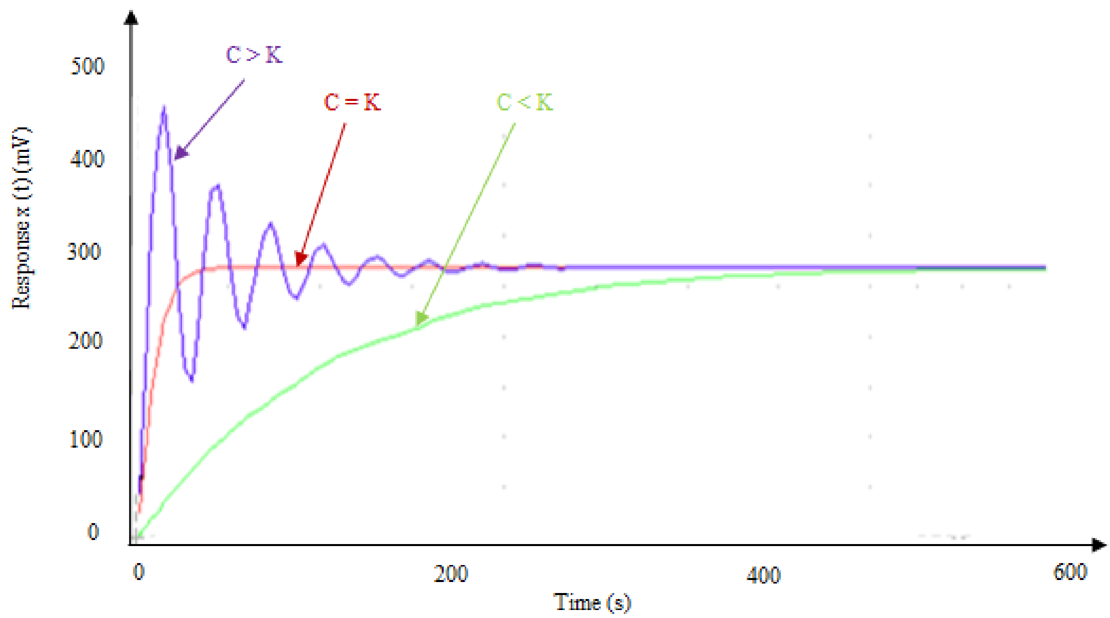


**Figure 10.** Response x(t) of the Age Group (65 to 90 years, and beyond) with Msystem = 18.60 kg

Furthermore, the response reveals that, a constant force is moderately adapted to, while one would expect a changing mass force to be detrimental to the system.

## 4. Conclusions

To conclude, damping, stiffness and mass distribution are critical and the main contributing factors affect the stability of the system apart from ageing, obesity, health deterioration, and lifestyle habits effects of the bone strength. Also it is known that with ageing the pores in the bone mass also decreases with closure of pores making it stiffer with almost zero damping. This results in osteoarthritis, rheumatism, including loss of energy and bone fractures including falls.

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