# Visualising kinematic of elastic Ossur ESR Prosthetic foot using novel low cost optical tracking systems

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**Abstract**

A novel method of measuring kinematics of elastic body is the subject of this investigation. Unlike kinematics of rigid body large elastic deformation tends to modify the dynamics of motion. In the case of amputee runner the change in kinematics of the foot depends on the stiffness, body mass and running beat frequency. Current measurement techniques, such as gait analysis assumes rigid elements. Currently there are inertia measurement unit (IMU) based systems that uses accelerometers and gyro to determine acceleration, velocities and orientations of the sensors. They are not capable of measuring changes in lengths or positions of the objects that they are attached to. For that reason predicting velocities and displacement by integrating acceleration is not always viable due to time step limits of the integrations that are necessary. Here a new optical device is developed and presented that is accurate and is practically error free to monitor Foot elastic deformation. In this paper the Dynamic elastic response of Ossur Running foot is being investigated using this device. The data generated show complete phase synchronisation with IMU but much better accuracy in terms of velocity and relative displacement of the feet due to flexure as a result of elastic response to Impulse.

## 1. Introduction

A normal leg with healthy ankle joint can generate, store and release energy during running and/or jumping activities [1]. For example a healthy individual can jump up in the air unaided from stand still by just using muscles and tendon complex in their legs and around their ankle. This makes the ankle act as a flexible actuator with variable passive and active properties that can adjust/tune itself in terms of stiffness and actuating forces during different motion scenarios.

On the other hand an Energy Storing and Returning (ESR) lower-limb prosthesis is a passive spring with fixed stiffness and damping characteristics. The size, shape and the materials used gives them the elastic properties to deform. Once force is removed, the energy is transferred to the body mass while restoring to its original shape. In practice these feet act like spring, which on their own have no ability to generate, store or release energy without external input. When it is combined with/or is attached to a body of finite mass/weight, it will possess dynamic characteristics such as natural frequency, mode shapes and damping, when energy is applied to it in the form of excitation, similar to a mass spring system.

This mass, spring and damper complex can now act as a transfer function of the device capable of absorbing, transforming and transferring different types of energies such as potential, kinetics, strain, or thermal energy between mass and the foot arrangement. This Phenomenon was already discussed in detail by Noroozi et al.[2–7].

### *1.1. Role of ESR foot*

The response of an ESR foot and mass system to cyclic excitation force will have two components:

i) a transient response which is the natural damped frequency which usually dies down.
ii) a steady state response which is an additional displacement which is the function excitation force and frequencies. And this is the steady state element of the motion.
iii) then there is an impulse element which again results in additional displacement of the mass causing the mass and foot system to loose contact with the ground. This part of the elastic response id function of the mass, The initial height, the beat frequency and the excitation impulse and its phase relative to its natural beat frequency.

However, for the steady state to be maintained, dynamic equilibrium of the all forces needs to be maintained. This requires additional input of energy to compensate for the loss of energy in one beat/cycle. If that is maintained the foot and mass will have a steady state vibration of constant frequency and amplitude which is given by equation 1.

$$X = \frac{\frac{F_0}{k}}{\sqrt{(1-\left(\frac{\omega}{\omega_n}\right)^2)^2+(2\zeta\frac{\omega}{\omega_n})^2}} \quad \text{.....................................................(1)}$$

Phase Angle:

$$\varphi = tan^{-1}\left[\frac{(2\zeta\frac{\omega}{\omega_n})}{1-\left(\frac{\omega}{\omega_n}\right)^2}\right] \text{.......................................................(2)}$$

Equation of motion:

$$x = x_c + x_p \text{..........................................................................(3)}$$

Therefore the general equation of motion can be presented as:

$$x = Ce^{-\zeta\omega_n t}\sin(\omega_n t + \psi) + X\sin(\omega t - \varphi) \text{ .............................(4)}$$

Where C = constant
$\zeta$ = Damping Factor
$\omega$ = forcing frequency
$\omega_n$ = Undamped Natural Frequency
$F_o$ = Force amplitude
$\varphi$ = Phase
t = Time
$\psi$ = Phase

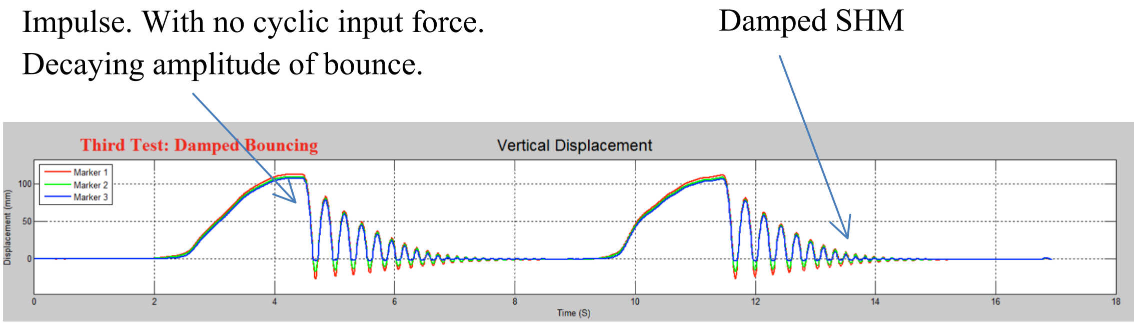
If this energy input per cycle is more than that the total loss of the system per cycle the additional energy supplied by the user, is transferred to the foot and later recovered and stored in the body mass. It will enable the foot and mass to slowly gain more potential/kinetic energy per-cycle until it is enough to cause the mass to eventually leave/lift off the ground.

In the case of a rigid mass and elastic foot system, the motion transforms from vibration to a bouncing motion "Trampoline effect" where both the foot and mass leave the ground and the motion reverts from Harmonic/cyclic motion to a Periodic motion with variable periodic beat frequency, that is a function of the boundary condition.

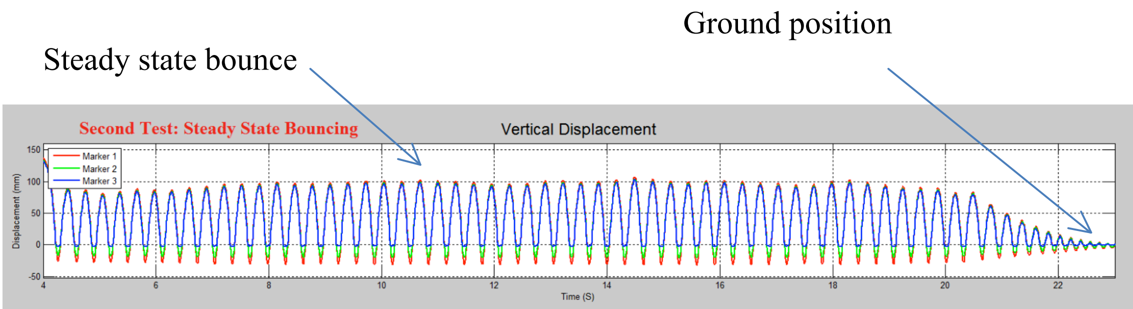
This paper investigates the kinematics of the elastic ESR foot and examines the relative motion and displacement of various points on the foot relative to the ground. Figure 1 shows three different motion scenarios of drop, steady state and adaptive response of the foot and mass system. Using optical transducers it is possible to accurately spate the displacement per beat, the ground position, the deformation due to elastic response. The displacement in mm, the time interval or beat frequencies and hence the full kinematics of the mass and foot system. Other kinematic parameters such as velocity or acceleration can be extracted from the data or the graphs presented in Figure 1 a, b and c below. The means of generating these kinematics graphs are the subject of the paper.

In this paper we propose a relatively novel low cost optical transducer system that accurately monitors, measures and tracks the elastic response of the foot to both steady state and impulse in order to better understand the inherent mechanism possessed by Ossur feet that allows the foot to act like a spiral coil spring, similar to those used in-traditional watched/clocks. The key feature of these springs is the ability to coil inward in a direction that has highest stiffness and absorb and transform that impact energy into high strain energy due to rolling inward, and recoiling and transferring the stored energy to the mass and in the direction of motion causing forward acceleration while transferring all the stored strain energy in to mass.

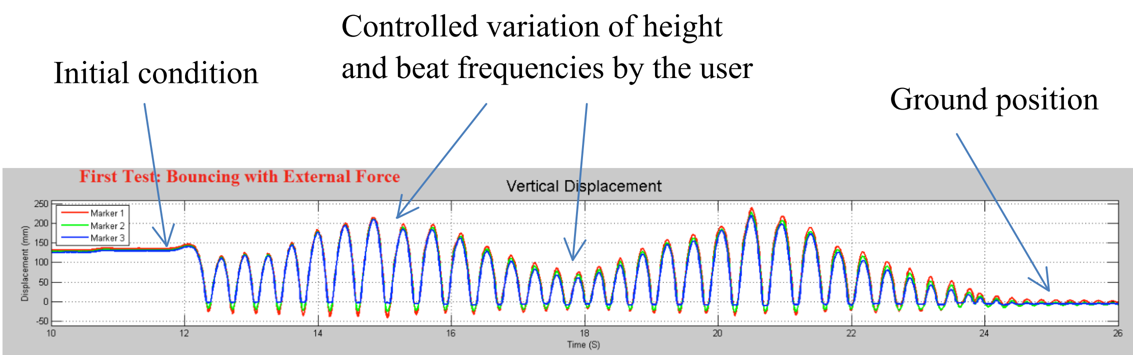
This paper presents a new and simple technology that can be used to track the kinematics of an elastic feet using slow motion camera, such as I-Phone, and Inertial Measurement Units (IMU)s and dedicated software that is capable of calibrating the image against distortion as well as frame by frame tracking the discrete markers, 3 in this case, in real time. This will enable the user to predict both static and dynamic properties of the feet such as range of motion, traction of ground contact point, running beat frequencies, the absolute and relative displacement and their rates of change with respect to time as well as instantaneous orientation of limbs using IMUs.




a) Impulse due to drop from a predefined height. Boune with decaying amplitude reverting to damped SHM




b) When steady state periodic force is applied to compensate for the loss of energy in one cycle and at the right Phase. Resulting in a stead state bounce.




c) Controlled by the user to either store more energy or recover energy to use elasewhere.

**Figure 1. The response of ESR feet to input buy the user resulting in the above 3 possible outcomes**

## *1.2 The issue of symmetry*

According to the literature gait symmetry is defined as body having identical behaviours / motion in both right and left limbs [(1)]. There are various kinematic and kinetic parameters that also plays a role when measuring gait symmetry. Some of the more obvious parameters are; displacement, speed, velocity, stride length, limbs rotation, joint rotation, weight, KE, PE, SE, forces, moments, impulse, stance time, swing times etc all of which play a role in running and can be used / monitored when measuring gait symmetry. (Symmetry index, ratio index and other statistical approaches).

Noroozi et al, both investigated the effect that lack of symmetry has on energy transfer and transformation rate between left and right legs and showed that people with symmetric gate consume substantially less energy over longer distances (walking or running) than those with un-symmetric gait. In the case of amputee runners this was proven both statistically by Hassani et al. [(5)], and experimentally and theoretically by Ong et al.

One approach to reduce the gap in performance between Unilateral and Bilateral amputees in longer distance race could be to improve their gait symmetry and socket comfort. The socket comfort is the subject of another investigation by the author. This paper's aim to present a tool that enable a more accurate measurement of the kinematics specially in the links are highly elastic. Such tool will offer a very cost effective means of obtaining a better measure of asymmetry of foot during activities and to learn from it. Monitoring motion using the proposed system will go a long way to help better understand how better dynamic equilibrium can be achieved and how the parameters mentioned above are effecting the elastic response such as speed, leg length discrepancies, and peak joint angles and position of the centre of mass. The proposed low cost system can readily measure basic gait data without the need for expensive and time consuming tools such as Vicon that usually require dedicated space. The proposed tool combined optical and IMU to measure both position as well as orientation of the limbs and prosthesis in real time.

## 2. Test Methods

A custom built test rig was designed and developed for this study. The test rig consist of a cross bar that is constrained to move vertically while remaining horizontal using two linear bearings at each of its ends. The cross bar is capable of carrying weight as high as the weight of an average person and is free to move vertically. The foot is mounted underneath the cross bar in a specially designed sliding mounting system that allows foot to be moved to the left, directly under and to the right of the centre of gravity of the loading system creating, under/correct/over-constrained/compensated load feet arrangements.

To track the motion three red dot markers were attached to the foot at key locations (Figure 2). It must be noted that there is no limit on the number of markers. It all depends on the objectives of our measurements. The markers are detected and tracked by a slow motion camera (120 frames per second) and an in-house image processing source code developed in MATLAB.

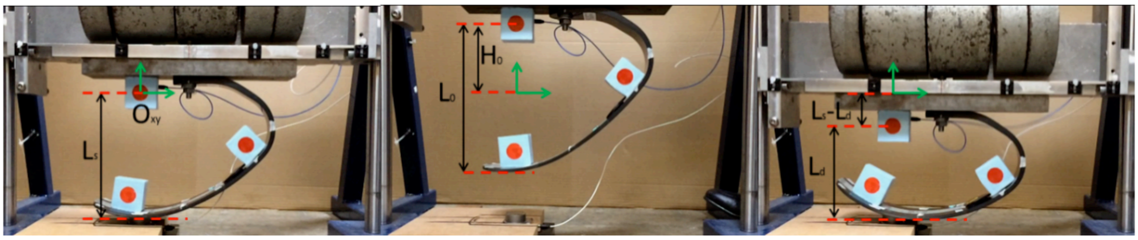



**Figure 2. The Marker used to track deformation as well as kinematics of the foot**

The camera location was fixed and image was calibrated in the 2D plane of motion using a custom made chessboard, as shown in Figure 3a. This was to compensate for any distortion due to intrinsic and extrinsic camera parameters and wide angle lens distortion as well as camera depth of field.

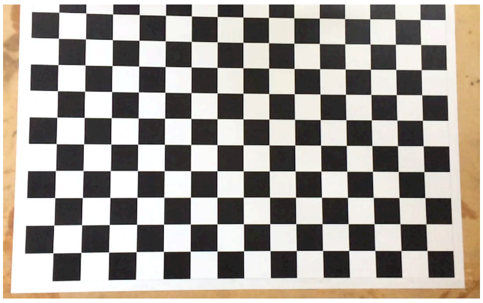
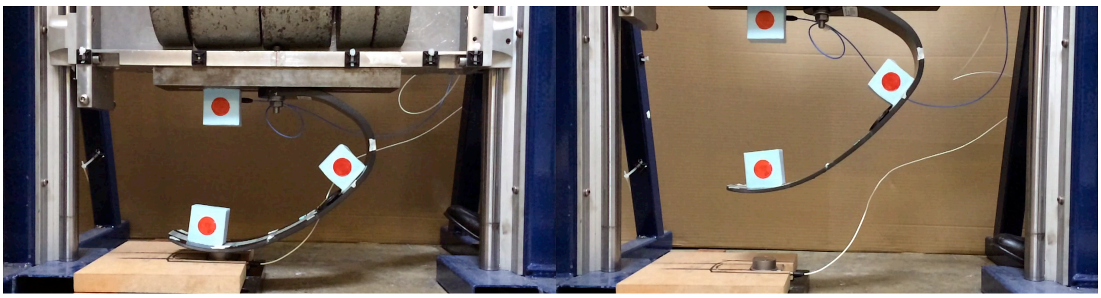
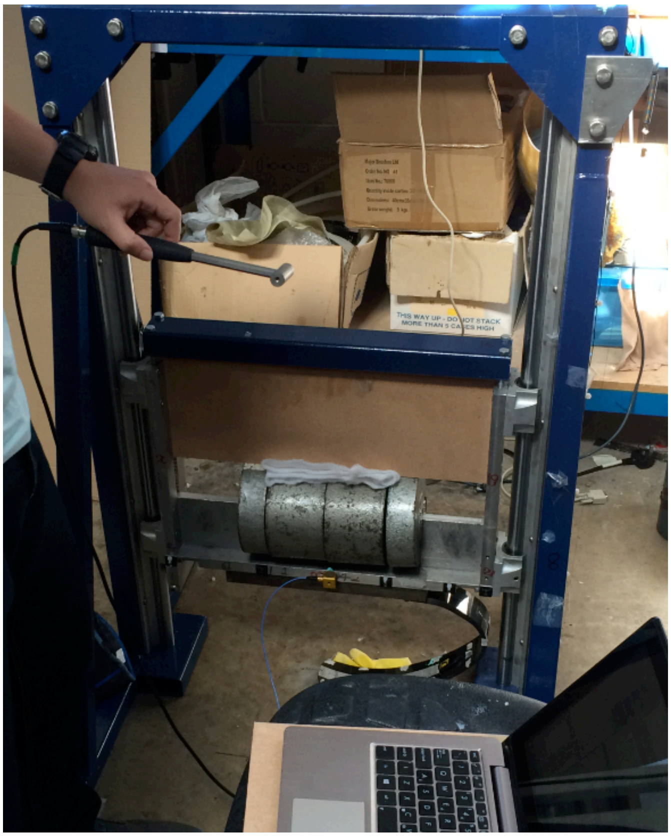


**Figure 3. The Optical correction checker board**

The foot was placed parallel to the camera. The rails in the cross bar limited the motion in a single 2D calibrated plane. This arrangement allowed absolute and relative displacement of every marker in terms of centre pixel coordinate to be accurately measured in mm. A three axes accelerometer was also attached next to first marker to measure the foot acceleration for validation purposes. A piezo electric impact force sensor was also placed underneath the foot as shown in Figure 4 to measure ground reaction force and another piezoelectric input force sensor was placed on top of the sliding crossbar to measure the hand's input force (its amplitude and its frequency). The input force should be less than/equal/greater than the input energy to the system in order to have three possible motion outcomes as shown in Figure 1. This way in was possible to measure input force at the cross bar, the ground reaction force on the ground as well as their relative phase, their frequency.



a) b)




c)

**Figure 4. Experiment setup showing impulse rig and the ground force sensor**

## 3. Results and discussions

Figure 5 shows typical data obtained from the proposed transducer system clearly showing the absolute position of the various red markers relative to the grounds and each other against time. The graph can be discretised and displacement, velocities and acceleration can all be extracted from these graph.

Similar to when using accelerometers and piezoelectric force transducers the system is capable of showing the impulse induced bouncing phenomenon which is what we call an elastic response to impulse synchronisation. This elastic response in not directly a function of mass and the stiffness as in vibration but it can be determined and controlled by the user as beat frequency that can be adjusted by the user. It can also show the transition point from bouncing to simple damped natural vibration which happens when energy is depleted and foot is in continuous contact with the ground.

What was observed here was that this natural frequency did not match any of those obtained using modal analysis of mass and foot system. It was later found that it is the natural frequency of the impulse rig system.

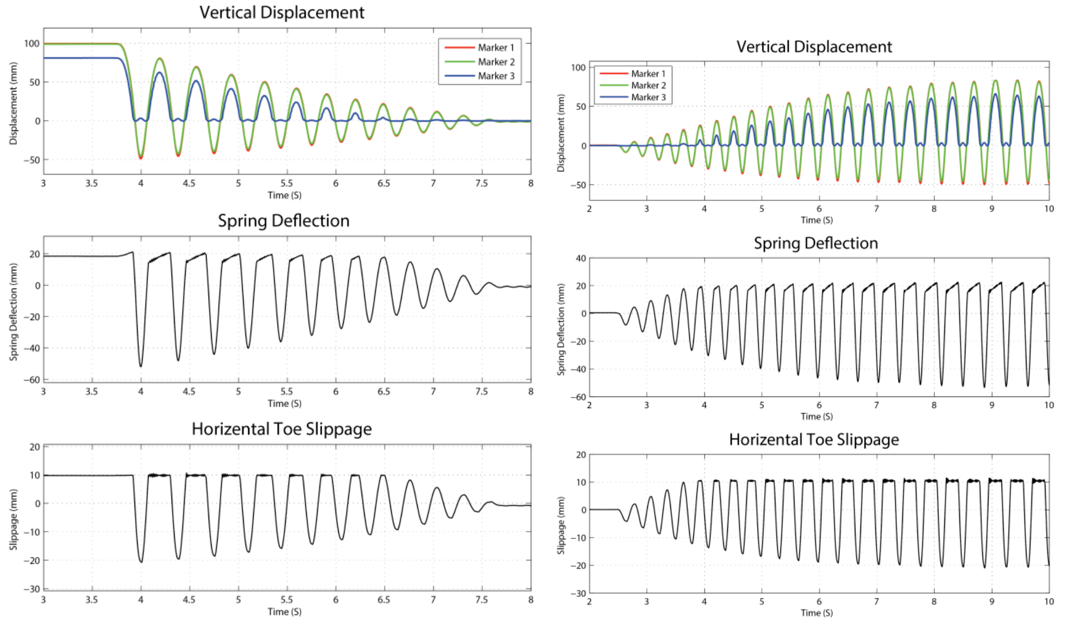



**Figure 5. Sample output from the optical system showing impulse**

Multiple "Ossur" composite energy return foot prosthesis (Ossur) were tested using this test rig and their elastic response to impulse was recorded. The figures 4 also shows two foot examples and Figure 5 shoes the typical measured outputs. In each case the motion was tracked in order to isolate and measure mechanical properties of individual feet such as:

- static deformation,
- dynamic deformation,
- beat frequency
- coefficient of restitution.
- effect of overhang/under hang/compensation (Over-stiff, Normal and under-stiff)

To measure the above a series of known weights were added on top of the cross bar attached to the prosthesis, as shown in Figure 4. In each case the static deflection under gravity of the ESR was measured. Later it was decided to use a fixed weight of 53kg for all the feet tested. This was due to the effort needed and the risks involved.

To measure the coefficient of restitution for the static system the prosthesis with a fixed weight attached on top was dropped from a fixed height (100 mm) and coefficient of restitution was calculated by comparing the initial drop height and return height after one bounce using equation 5 and values of h and H obtained using the proposed device.

$$C_r = \sqrt{\frac{h}{H}} \quad \text{.....................................................} (5)$$

Where, $H$ is initial drop height and $h$ is maximum height after first impact.

To measure dynamic deformation, the cross bar was initially lifted to a known/predetermined height and then released/dropped. The displacement between first marker and third marker was measured during static equilibrium, in the air and just before the drop and then and after the drop at different interval to cover full range of motion. The drop caused to foot to experiences a much larger deflection due to impulse, the duration of which can also be extracted from the image in order to measure the average acceleration, velocity and the impact force due to drop test.

To investigate the kinematics of elastic feet during steady state energy transfer cycle between the body mass and foot (spring) system a synchronization test was performed and results can be seen in figure 1 & 5. For this part of the experiments 3 different feet were tested, the softest-Lo1, the hardest-Lo9 and the intermediate-Lo5 feet all carrying a 53kg mass. In all 3 cases the mass was excited from static equilibrium position by applying cyclic force with frequency close to the system natural frequency until resonance and this was maintained until enough energy was stored in the mass to cause the foot and mass to lift off the ground, similar to trampoline.. Attempt was then made to apply the force at a desired beat frequency and magnitude that was necessary to maintain a steady state beat bounce at a desired height.

Using the same mass with all 9 foot categories makes it possible to investigate how a target beat frequency can be achieved for a give energy state of the system. This means if an amputee was free to choose any of the 9 weight categories for running he would probably choose a different foot for short distance sprinting and may be a different one for longer distance running.

The data presented in Figure 6 Show that stiffer foot is more beneficial for short distance running when strength and fitness dictates the outcome in both Unilateral and bilateral amputee sprinting. In contrast the opposite was true for longer distance sprinting.

This study showed that the optical transducer proposed here clearly show the elastic kinematics properties of the feet and allows more accurate measurement of displacement and velocities as compared to accelerometers signal processing which requires integration to measure velocity or displacement, which can be inaccurate due to time interval involved in integration. The camera used for this purpose was an ordinary I-Phone camera which proved reliable enough in terms if speed and resolution as a low cost motion assessment system.

Care must be taken not to confuse the damped natural frequency of the mass and foot system with that obtained when foot is in the impulse rig. In the latter case the natural frequency of the rig dominates the dynamic of the foot and causes the foot deformation to follow the motion of the rig imposed on the foot through the sliding cross bar. This is due to large differences in the stiffness between foot and the impulse rig.

To demonstrate this a sample modal analysis of the assembly shown conducted and its Frequency response functions are presented in figure 6-a,b,c below.

| | 1st Natural Frequency Z-dir | Damping (%) |
|---|---|---|
| 1LO free-free | 3.90 | 1.93 |
| 1LO constrained | 20.7 | 1.82 |
| Impulse test rig | 20.1 | 5.46 |

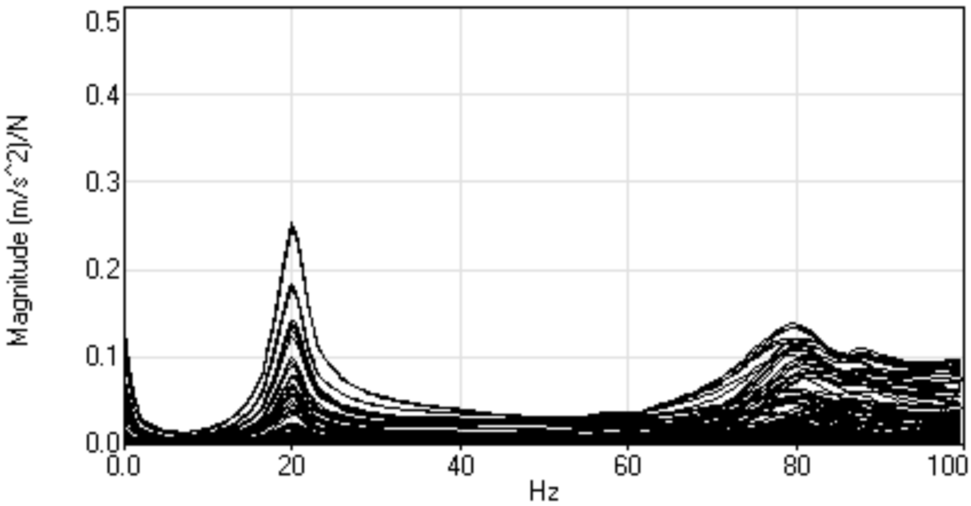



**Figure 6a FRF of impulse test rig shows the structural mode @ 20.1Hz**

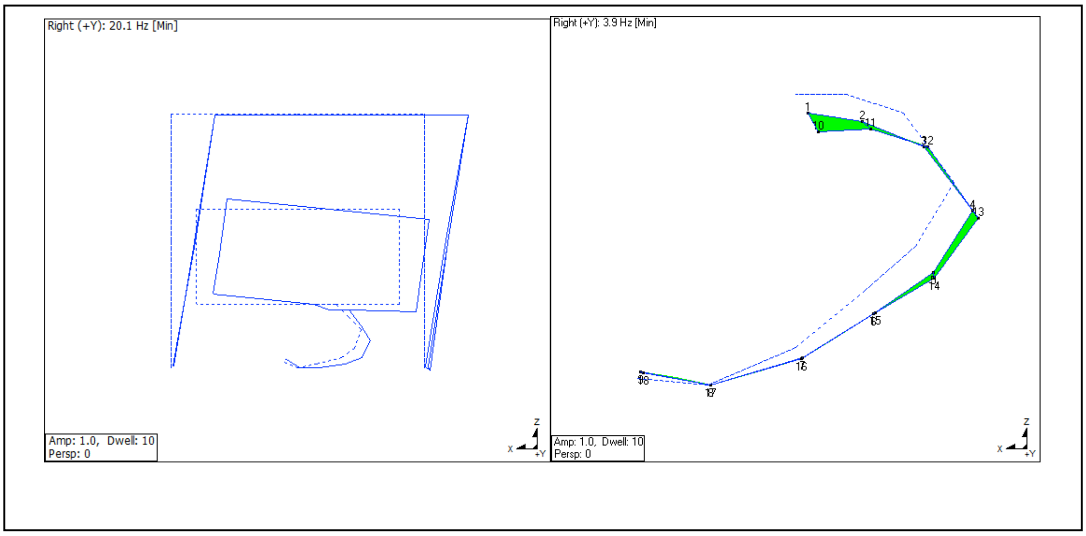



**Figure 6b First test rig mode in x-direction @ 20.1Hz**

**Figure 6c First bending mode of 1LO at 3.9Hz with free-free boundary condition**

The modal analysis of the rig shown above, shows that the natural frequency of the rig. It shows that it is practically independent of the presence of the foot due to the large differences in properties. For that reason performing modal analysis of the foot when mounted in the rig is practically meaningless as the modes obtained belong to the rig. Study was also conducted by looking at the trace of the acceleration after the impulse has stopped and motion was reverted to Natural damped vibration. It was noticed that even then the Damped natural frequency of the foot in rig was not the same as calculated using modal analysis [(2)].

To find static and dynamic deformation of the feet all of them except foot No-7 were tested in the test rig using the same weight of 53kg and initial drop height of 100 mm. As shown in the chart below Figure 7 the feet with higher stiffness showed less static and dynamic deformation, hence lower energy transformation implying better short sprinting ability.

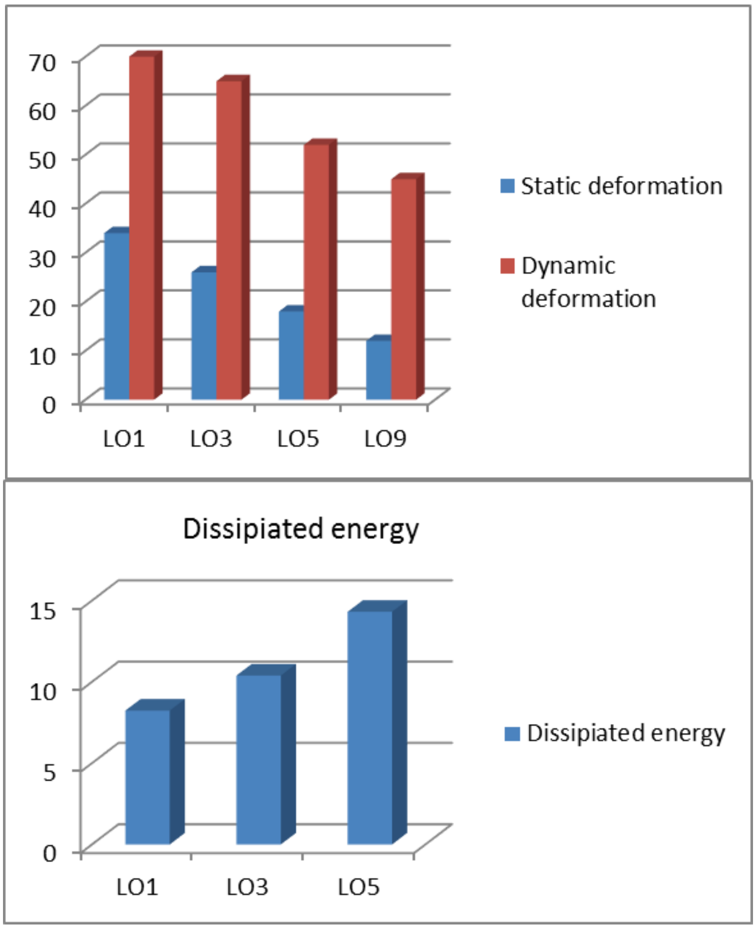



**Figure 7. Showing the static and dynamic deformation of the foot as well as energy dissipation rate in mm and Jules**

The displacement measurement would allow the energy calculation showing the energy dissipation of the feet. Using this system it was possible to show that using the feet with the average weight suggested by the manufacturer, still resulted in a similar energy dissipation rate when using larger mass and higher grades of feet while testing feet 1,3,5 with 42,53 and 73 kg respectively.

Similar to the SHM, the transient and steady state beat frequency are function of the stiffness and mass but they are also function of the height and the input Force(strength). Figure 8, below show the beat frequency increases with stiffness. But they are initially the same, in both transient (Drop test) and steady states (trampoline effect). It should also be noted that the foot LO1 is overloaded and LO9 under loaded when using a 53kg mass.

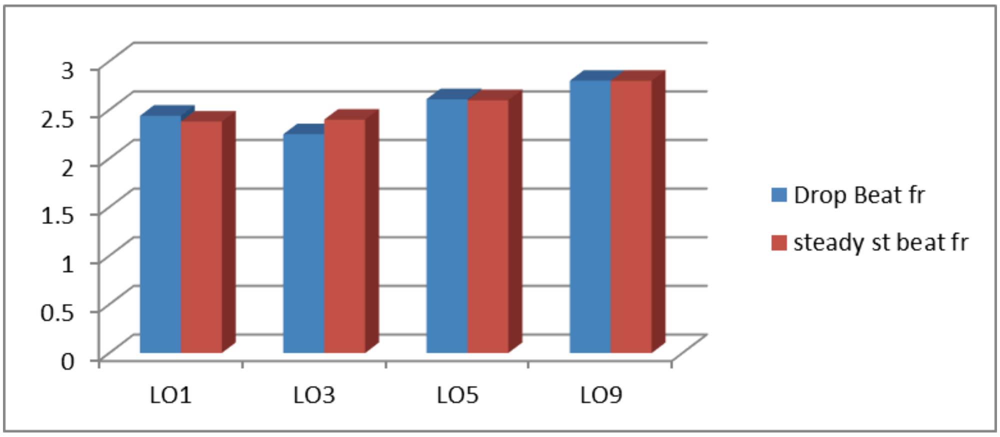



**Figure 8. Comparison of drop beat frequencies of different foot using the same mass.**

## 4. Discussion

The data presented shows the combination of IMU and Optical tool work well to extract Key kinematic data in a very cost effective and approachable level. It will remove the need for dedicated spaces and expensive gait analysis software and camera system.

The data is relative, as it is with other tools, but using basic correction and calibration system with using basic experiment design, simple dedicated artefacts and motion protocols, one can achieve a substantial levels of good information that can help practitioners with all kinds of data from monitoring motion data to joint kinematics and kinetics as well as kinematics of elastic bodies. Etc.

## 5. Conclusion

The data obtained validated the initial speculation that simple motion tracking in two plain will be just as valuable for performance assessment and monitoring as any expensive tools currently in the market. Making motion analysis both affordable and accessible to all.

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