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SIMULATION OF PERFORMANCE ENHANCEMENT OF BI-LATERAL LOWER-LIMB AMPUTEES THROUGH IMPULSE SYNCHRONISATION WITH SELF SELECTED RUNNING STEP FREQUENCY

Siamak Noroozi[1], Abdul Ghaffar Abdul Rahman[2], John Vinney[1], Ong Zhi Chao[3]
Khoo Shin Yee[3]

[1]School of Design, Engineering & Computing, Bournemouth University, Poole, Dorset, BH12 5BB, UK
[2]Faculty of Mechanical Engineering, University Malaysia Pahang, 26600 Pekan, Pahang, Malaysia
[3]Department of Mechanical Engineering, Engineering Faculty, University of Malaya, 50603 Kuala Lumpur, Malaysia

Phone: 01202 965554, Fax: 01202 965314,
Email: snoroozi@bournemouth.ac.uk

ABSTRACT

Current method of enhancing the performance of a bilateral amputee runners using energy return prosthesis is rarely linked to the system dynamics. In this paper a simple simulation is used to show that if a self selected running step frequency could be synchronized with dynamic elastic response of a mass spring system extra gain in height or faster take off velocity can be achieved which results is higher state of energy equilibrium that is more favourable to running activity. Current method often relies on physiological methodology, making the differentiation between the contributions from the biological and the prosthetic element of the below-knee amputee athlete difficult. In this paper a series of mass and composite foot system are modelled based on a combination of mass, spring and damper arrangement to study the effect of gravity, mass, stiffness, damping and inertia on the dynamics characteristics of prosthesis and how human can instinctively detect the natural elastic response of such system both to cyclic excitation and impulse through self selection of frequency or impulse.It will be demonstrated that if the natural characteristics of a system are identified and synchronised with the physiological gait behaviour of a runner, performance enhancement could occur that can be stored and controlled at will by the user. In the case of a bi-lateral amputee athlete with near symmetrical gaitit can result in steady state running which can be beneficial over longer distances.

***Keywords*:** Amputee, Prosthesis, Lower-Limb, Foot, Energy Return, Dynamics

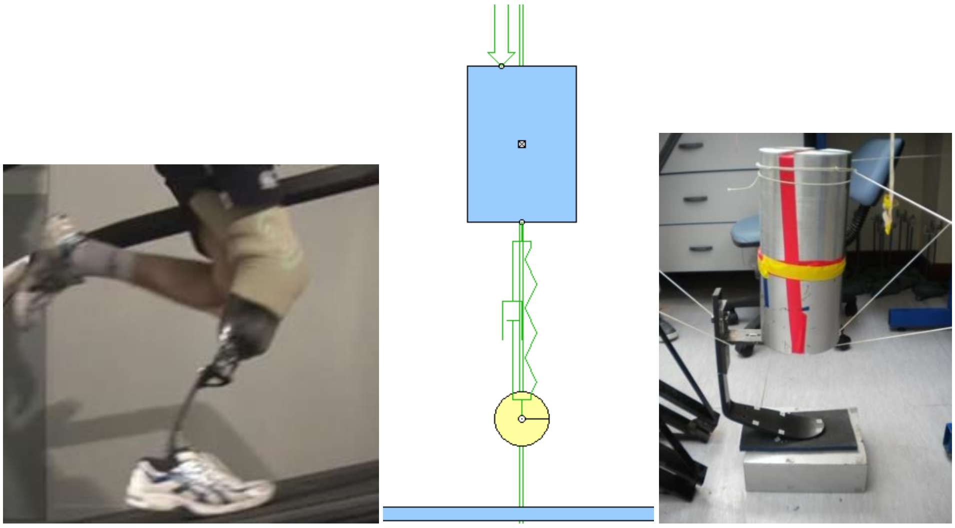
INTRODUCTION

The desire of individuals with a lower-limb amputation to participate in sports and the high demands of athletics, have resulted in the development of energy-storing-and-returning (ESR) feet, capable of storing energy during stance and returning it to the individual to assist in forward propulsion in late stance(Versluys et al., 2009). ESRs have been in use for amputees commercially since 1985(Michael, 1987).Since the introduction of the first specialised prosthetic sprint foot in 1996, no significant design changes have been made to the original design(Lechler, 2005).Currently, very little data is available regarding the dynamic characteristics of ESR feet to sustain a conclusive argument for or against their performance enhancing capabilities. Grabowski et al. (2010) highlighted that there is very little knowledge of the dynamic response of the spring like prosthesis and more research is needed to better understand the contribution that enables the amputee to achieve top speed. Czerniecki (2005) found that a typical ESR foot has an efficiency of as high as 95% while the ankle can generate 241% energy return. This has led to the conclusion that prosthesis is fundamentally restorative technology that still falls a long way short of replacing the mechanical performance of the biological limb (Nolan, 2008;Dyer et al., 2011). Weyand et al. (2010) examined the mechanics of running and concluded there are three key parameters associated with running: 1) how fast the limb can be re-positioned for the successive step; 2) the forward distance the body travels while the foot is in contact with the ground; 3) how much force the limb can apply to the ground in relation to body weight. It was speculated that if any of these parameters exceeds what is possible in human biology, enhanced running speed will result. Bruggemann et al. (2008) conducted a series of tests to establish if ESR feet can enhance performance. Physiological indicators were used to track energy efficiency and link the results to the performance of the feet. It was concluded that performance could be enhanced, particularly in bilateral amputee sprinting. Buckley et al.(1999 and 2010) described the mechanism of steady state running using ESR feet to a series of exchanges between potential, kinetic and strain energies of the leg and body system. However, no consideration has been given to the damping of such systems even though at the extreme of motion damping is the only force resisting biological forces generated by the athlete.

Hunter et al. (2005) studied the link between ground reaction force, impulse and kinematics of running during acceleration. It was shown how ground reaction force can accelerate the mass and how impulse can assist running. Keogh (2011) has concluded that the results of studies on amputee sprinting tend to indicate that improvements in running-specific prosthetics have contributed to the enhanced performance of Paralympic amputee runners and that the question of whether such improvements are fair and/or consistent with the Paralympic or Olympic ethos. The debate of fairness of lower-limb prosthesis running technology in sport has recently been raised (Dyer et al., 2010). To appreciate the effect /influence of ESR prostheses in running, all aspects of their static and dynamic response need to be studied and understood.

METHODS

This paper simulates the effect of impulse due shock loading of a mass spring system, similar to that of a human running when wearing socket that is attached to an ESR composite foot. (Figure 1a, b&c).



a) b) c)

Figure 1. a) Amputee running on the Elite Blade(Endolite®, 2011), b) An equivalent working model 2D representation and C) showing a mechanical equivalent.

Hypothesis

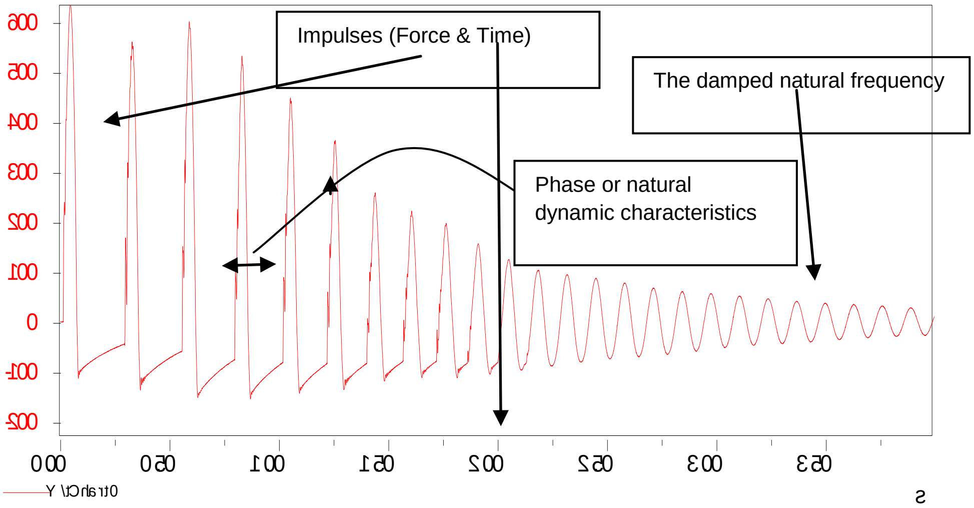
In this paper it is hypothesised that walking or running at a frequency that matches either a relevant natural frequency or the elastic dynamic response of the combined ESR foot and body mass system can provide a mechanical advantage if synchronised correctly. In this initial study, dropping a mass that is attached to an ESR foot is simulated here to show the effect of impulse on the system, its cyclic nature and the loss of energy and decay in amplitude. It is also speculated and later proven that human can instinctively detect both the natural frequency or the dynamic elastic responses of a mass spring system weather it being sinusoidal of impulse driven.

Working model 2D was used here to simulate two cases where the user can instinctively detect the frequency and the phase in which he or she needs to apply force or effort to create either a steady state response or increase and store energy in the system to gain more height or velocity or amplitude. This study is conducted in 3 phases, 1) mechanical drop test. 2) WM2D simulation, and,3) Mathematical simulation using DasyLab.

1)

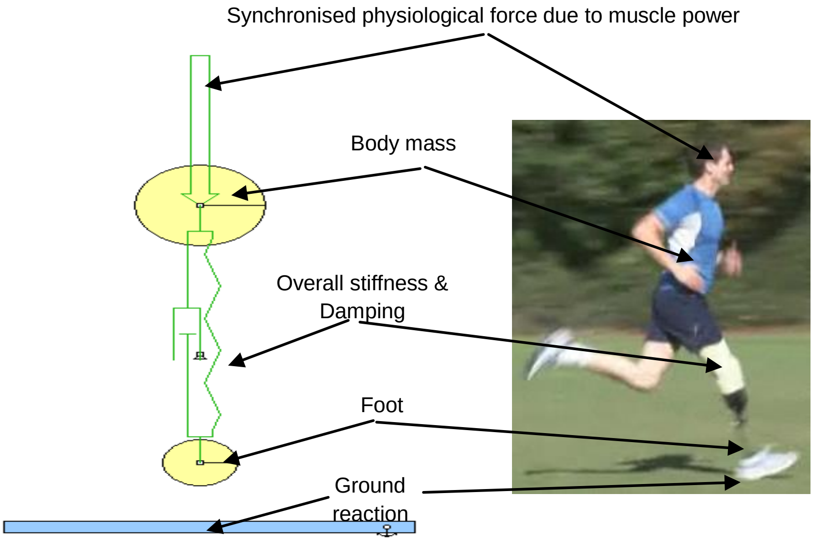
A solid mass attached to a composite prosthetic foot, forming a system, as shown in Figure 1C was used to study the response of the system to an impulse due to dropping it from a height. A series of tests were designed and conducted and a sample output of this test is shown in Figure 2a.

The graph of the response shows that as a result of bouncing cyclic pulses are generated. However, as it can be seen from the graph without any additional input the amplitude of the height decays due to damping and other losses in the system.



a)

It can be seen that the effect is an exponential decay in pulse amplitude and pulse frequency & period (time between two successive impulses) which after a while reverts to a damped natural frequency before stopping. However, drop test alone cannot simulate the effect of body's ability to generate force at self selected frequency and amplitude that matches that of the impulse. Also unlike human, the deadweight used in drop test experiment do not possess intelligence in the form of ability to generate controlled sinusoidal or cyclic input force that can complement the effect of residual inertia or gravity effect of the system.



a) b)

Figure 2. a) Mass-spring-damper simulation of b) body and prosthetic ESR system (Endolite®, 2011).

Closer study of the above graph show that if the loss of energy in once cycle can be matched by an equivalent input energy through human effort and is applied at the right phase it can result in three possible outcomes. 1) Decaying amplitude, 2) A steady state response and 3) An increasing PE in the system due to extra gain in height. And shown in the DASYLab simulation shown in Figure 3.

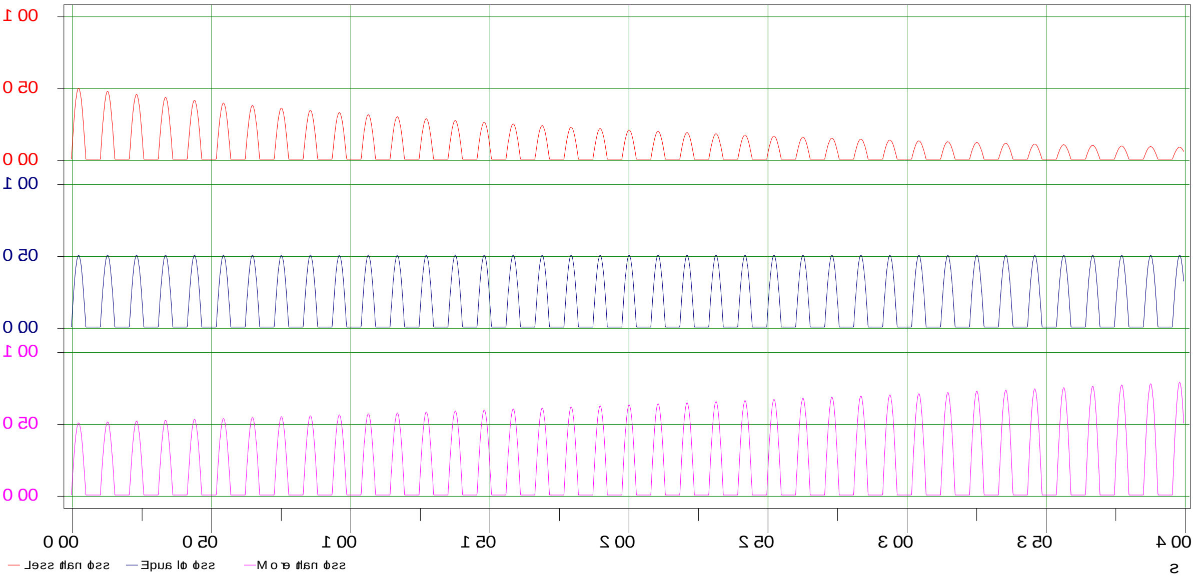


Figure 3. DASYLab simulation.

To simulate the effect of human replacing the deadweight and also demonstrating that human can instinctively pick up natural modes of vibration or feel the elastic dynamic response due to impulse, a similar system, that is also analogous to the mass &spring system, shown is figure 1c, was created using the WM2D simulation system. This highly idealised system closely represents the mass spring system shown in Figure 1C. However, in this model there exists as arrow representing an external input that can be triggered by the user. This system was used to repeat the simulation shown in Figure 2 but this time all the timing, phase, load intensity and duration are controlled by the user.

This model was capable of demonstrating 2 key elements that is crucial in any able and disable bodied athletics and sports and that is

a) The input equal or more than loss in the system results in accumulation and storage of energy that can later be recovered at will.
b) The ability of human to detect the dynamic response of the elastic system and synchronise with it to enhance performance.

A practical application of this system can be shown in the form of a swing or trampoline.

In both cases, if at the end of each swing or travel, when the forces are is the state of momentary equilibrium, an additional sinusoidal/cyclic input force, such as push or human effort (Push of a swing or hip and leg activity) will act on the body un-resisted except by the damping force, and depending on its magnitude can result in energy storage.

- Stead state motion. That is when the input energy is applied in phase and its value is equal to the loss of energy in that cycle.
- Increasing amplitude of the swing if the input energy is applied in phase and its value is larger than the loss in that cycle. This results in a higher energy state of the system in the form of larger swing amplitude until a new equilibrium is reached.

- Decreasing amplitude of oscillation if the energy is applied either out of phase or in phase but its value is less than the loss in one cycle. In either case it results in motion suppression.

MECHANICAL SIMULATION using Working Model 2D

The phenomenon, that can help or assist a bilateral below knee amputee runners using ESR blades to run faster, or to help an able bodied athlete using trampoline to gain extra height advantage, on a person using trampoline or swing to gain height is presented here using working model 2D simulation software. A simple 2 mass spring and damper system, as shown in figure 1b,capable of representing both single and two degrees of freedom system that can simulate different stages of a unilateral amputee running or able body bouncing on a trampoline, was used to show the effect of load input synchronisation on the response.

Figure 4 show the comparison between the simulated and real data from a drop test experiment. This was done to validate realistic nature of the simulation model employed.

This system was first used to simulate the effect of gravity alone on the dynamic response of the system when it was dropped from a height.

1) Drop test under gravity force alone,

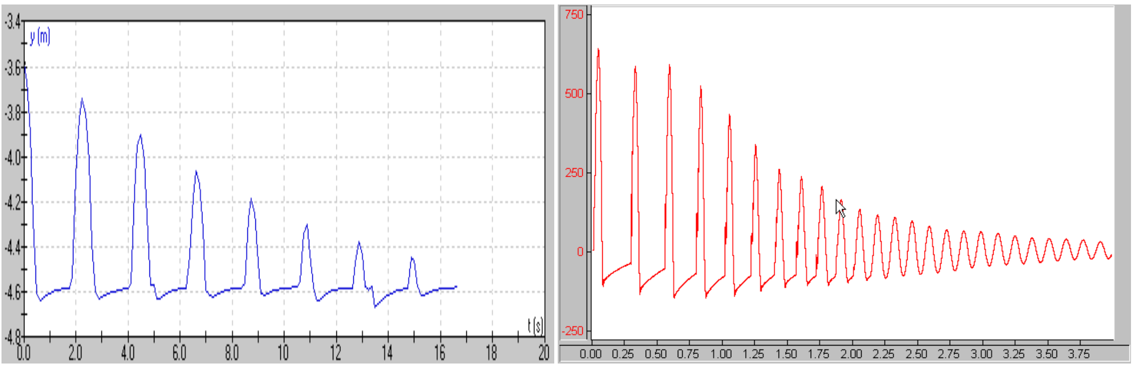


Figure 4a, 4b shows the comparison between the displacement profile between real and the imaginary system

2) Under cyclic synchronised impulse.

In the second simulation the model was used to simulate the body when it was acted upon by a mass-less force representing normal body force/muscle power or human effort. The frequency and intensity of this applied force was left at user discretion, to take his or her own time to detect and synchronise with to establish or create a steady state impulse or bouncing action. Figure 5 shows a close to steady state response that could be achieved in a short time by user intuitively detecting and synchronising with the natural dynamic characteristic of the system. Such a cyclic response can only come from cyclic muscle power that can be generated by the athlete to perform a bouncing or running action and as result of burning calories and other physiological reactions. Figure 5a & b. The effort synchronised intuitively close to steady state impulse creation representing bouncing or hoping or running action.

3) Asynchronous application of the load.
In the asynchronous simulation load was applied both in synch and out of synch with the dynamic characteristics to control various phases of an activity, such as acceleration, slowing down, accelerating again and maintain the speed.

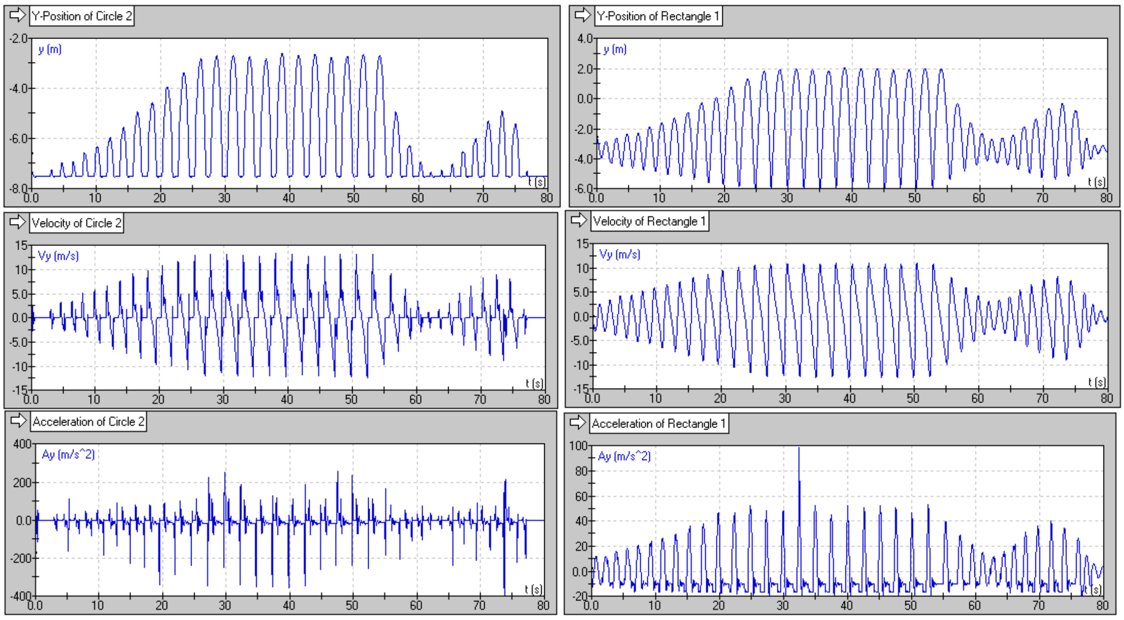


Figure 5. Displacement, velocity and acceleration of the system during Dynamic Elastic Response to Impulse Synchronisation (DERTIS)

Figure 5shows displacement, velocity and acceleration of the system during Dynamic Elastic Response to Impulse Synchronisation (DERTIS) showing increasing, steady state and fluctuating energy state of the system. At the terminal or later stages of a run a steady state can be achieved when a constant force, effort or energy is applied with magnitude equal to the loss of energy in one cycle.

This effect lends itself to it being used as a design tool that allows better tuning of mass to prosthesis that matches for impulse synchronised gait frequency. Closer examination of the simulation system and the plots show that in the absence of any external force or effort by the athlete, the motion generated due to drop from a height results in some bouncing motion with decaying amplitude, then reverting back to simple damped vibration at its natural frequency until it stops.

However if a cyclic energy is applied by the runner through the application of a mass-less force (body forces, muscle power, Physiological inputs) with a magnitude that is more than the loss of energy in one cycle, is applied in phase and at impulse frequency that matches the step frequency, it can result in two other distinct possible outcome. Therefore, depending on the relative size of the force, masses, damping ratio, stiffness, frequency and phase it can result in:-

1) It can result in extra gain in height due to the gain in the amplitude of the ground reaction force causing faster take off speed resulting in higher KE which results is higher PE. If this action is sustained energy will be accumulated, stored and can later be recovered by the system

2) It can stop the motion if the force is applied at the wrong the time or phase of the motion, resulting in the reduction in ground reaction force, lower take off velocity and loss of potential energy as seen in Figure 6.

This simulation also demonstrated the human ability to detect and synchronise with any cyclic force or motion within limit. Here the synchronisation is performed by the authors using simple mouse action that was synchronised with the motion of the image/body showing that normal human being can inherently identify any natural rhythm and is able to actively synchronise his effort to gain mechanical advantage.

MATHEMATICAL MODELLING

The hypothesis discussed above was further modelled mathematically to substantiate and validate of this synchronisation argument. The aim of this theoretical study is to investigate how phase between input force and cyclic impact frequency can result in accumulation and storage of energy that can later be recovered at will, hence minimising energy consumption by the runners.

This section presents the mathematical simulation of the same system, initially suggested by Rahman et al. To represent the elastic dynamic response of the mass foot system to a cyclic impulse load that matches the profile of the natural frequency of a dominant mode. In this study it is assumed that the motion of the body is reduced to a single degree of freedom (DOF) mass spring system dominated, as shown below, by the 1st bending mode frequency of 4Hz, which was extracted from modal analysis of the ESR presented elsewhere (Noroozi et al., 2011).

Ignoring air resistance, and some alignment issues, etc, the motion of the system is controlled by three forces that collectively contribute to the motion response and the total displacement of the mass & spring system:

PART I The impact contribution due to initial velocity (*v_0*) when the foot touches the ground.

PART II The constant body weight (*mg*) generating a new static equilibrium position.

PART III The cyclic load (*Acosωt*) generated by the body movement due to running or effort.

If the above forces are all acting at the same time the resultant equation of motion can be given by:

$$x = \underbrace{e^{-\sigma t}[x_0 \cos\omega_d t + \frac{v_0 + \sigma x_0}{\omega_d}\sin\omega_d t]}_{\uparrow\ \boxed{\text{PART I}}} + \underbrace{\frac{mg}{k}}_{\uparrow\ \boxed{\text{PART II}}} + \underbrace{\frac{P\cos(\omega t - \phi)}{\sqrt{(k-\omega^2 m)^2 + (c\omega)^2}}}_{\uparrow\ \boxed{\text{PART III}}}$$

x = displacement (m)

x_0 = initial displacement (m)

t = time (sec)

ω_d = First bending damped natural frequency (rads^{-1})

v_0 = initial velocity (ms^{-1})
σ = decay rate (rads^{-1})
m = mass (kg)
k = effective spring stiffness (Nm^{-1}) or (kgs^{-2})
g = constant of gravity (ms^{-2})
P = excitation force (N) or (kgms^{-2})
ω = cyclic movement generated by body movement/ excitation frequency from body (rads^{-1})
ϕ = phase angle (rad or degree)
c = damping (kgs^{-1})

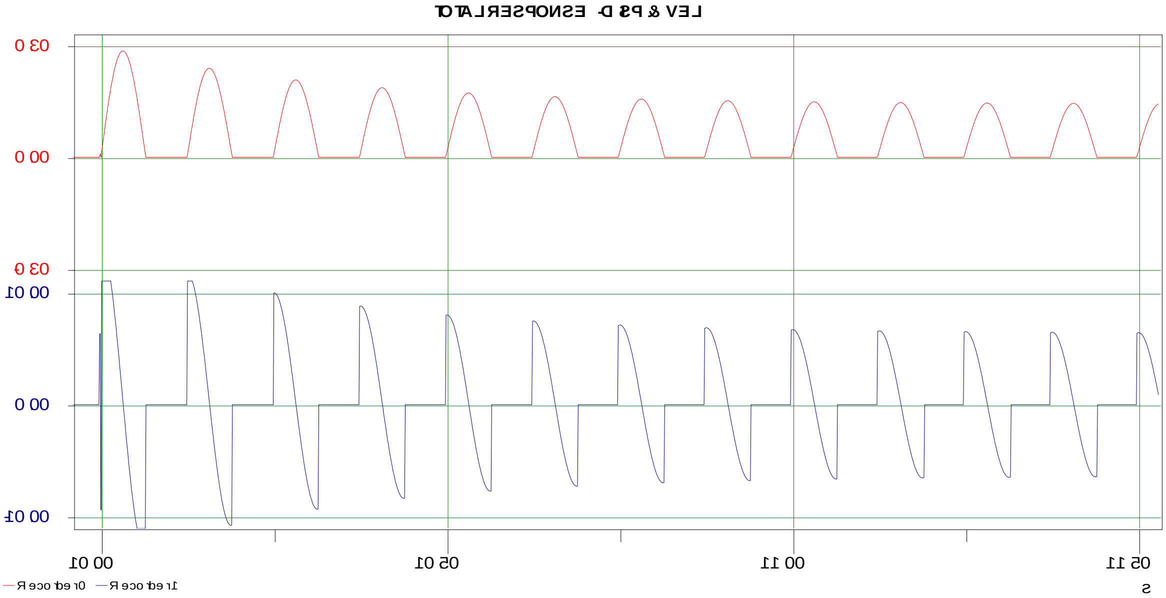


Figure 6. Total response

Figure 6 graphically describes the two main elements of the three responses. The gravity is a constant horizontal load, omitted from the above graph. In this simulation the displacement is measured from the ground level with downwards displacement being positive. The sinusoidal curve is only valid for values of Z > 0 where the motion is governed by the mass-spring-damper system. For Z < 0 the motion of the mass is governed by the gravitational field only and is acted upon by gravity only (a horizontal line, omitted here). The first half of a sine wave is used as impulse force representing ground reaction force which is when the foot is in contact with the ground.

Equation (1) contains three parts: **Part I** is dependent on the height of the fall; **Part II** is dependent on the weight of the body, as the body has very little or no ability to control its fall under gravity or free fall condition; **Part III**, however, can be generated and controlled by the body using muscle power or rhythmic or synchronised effort. This cyclic/synchronised muscle power comes from energy due to burning body calories (internal metabolic actions), etc. The frequency of this simple cyclic force canbe determined due to intelligence and other senses that allow passive determination of the natural frequencies or dynamic characteristics as shown previously. However, for this mathematical simulation to enhance performance the body needs to generate a force with varying intensity equivalent to a half cycle of a cosine wave (Figure 6), starting from the instant the foot hits the ground, and with frequency equal to the natural frequency of the first bending mode of the vibration.

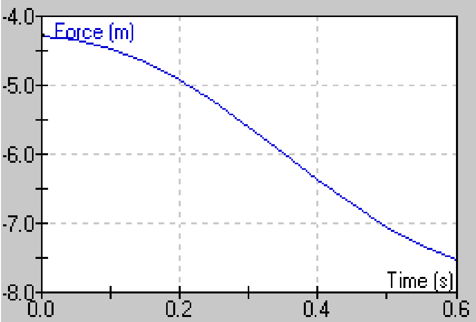


Figure 7. Force intensity profile needed to generate additional take-off velocity and height.

To achieve a sustained motion:

a) The resistance due to stiffness K will be cancelled by the inertia resistance $m\omega^2$ i.e. ($K-m\omega^2=0$), leaving the force A resisted only by the damping resistance force, $c\omega$.

b) The phase angle ϕ must be equal to 90^0, making the response to be almost in-phase with the response due to impact (response Part I). This will, in effect, cause a higher take-off velocity.

c) The phase is of paramount importance because wrong phase will cause the mass to work as a damper and against the motion slowing or stopping the motion.

The dynamic simulation of the characteristics and response of a typical case, consisting of a mass and spring system being dropped from a height and then acted upon by a cyclic force, in synchronisation with one of its natural frequencies is presented below. The actual physical quantities, such as mass, damping factor, decay rate mode shape and frequency were all obtained from the experimental modal analysis conducted prior to this work (Noroozi et al., 2011). Below is a typical calculation to show the effect that the synchronisation has on the performance of the foot:

$V_o = 4\ \mathrm{ms}^{-1}$	This is due to free fall of a 55kg mass from a height of 0.08m
$\frac{P}{m} = 5\cos\omega t$	Half the body weight
$\sigma = 0.25$ Hz	The decay rate extracted from the experimental modal analysis tests
$\omega_d = 4$ Hz	First bending damped natural frequency
$m = 55$ kg	The body mass
$K = 34\ \mathrm{KNm}^{-1}$	The effective stiffness, extracted from the SHM theory
$\omega = 4$ Hz	The cyclic frequency of the effort generated by the body movement of the athlete.
$\phi = \tan^{-1}\left(\frac{2\sigma\omega}{\omega_d^2-\omega^2}\right)$	The predicted phase required

Therefore, the following formula is obtained from equation (1):

$$x = 0.158e^{-0.5\pi t}\sin(8\pi t - 5.8^{o}) + 0.016 + 0.126\sin\omega t$$

Figure 6 shows the displacement and the take off velocity as a result of synchronised input in to the system. In this mathematical simulation the results show that the take-off velocity due to impact alone is increased substantially when superimposed by a synchronised cyclic/sinusoidal load, generated by the body. This proves that, synchronised cyclic input force adds to the impulse which can help to increase height due to higher take-off velocity. This gain in height results in additional gain in potential energy which is available to the athlete to use during the next foot strike giving larger impulse hence more energy in to the system and this continue to increase until the new equilibrium is reached.

A unilateral amputee, generating the same cyclic load, will only gain height on every other take-off from the ground. This can result in lack of symmetry which limits the positive effect of the synchronisation with natural dynamic characteristics. However, in the case of a bilateral amputee this results in conservation and storage of substantial energy that can manifest its existence towards the end of the race when most runners are tired. During this phase of the race, the runner is running at a steady state speed resulting in both perfect synchronisation and symmetry resulting in minimum losses of energy.

DISCUSSION

The mathematical and experimental results demonstrates that if the impact frequency due to self selected running frequency is synchronised with the natural bending modes of vibration, the ESR foot responds like a trampoline resulting in higher take-off speed and higher potential energy storage in the system. Also, every mass spring system has its own natural dynamic characteristic that is unique to that arrangement. The human body and brain can naturally detect these natural modes. If these modes are identified and subsequently synchronised with the self selected (predicted) running frequency, it can enhance performance, as shown in this paper, resulting in faster take-off speed and extra gain in height. This stored energy can assist runners during the latter or steady state phases of their chosen running event. Therefore, bi-lateral amputee athletes with close to symmetrical gait can synchronise their running frequency and effort with the natural characteristics of their prosthetic limb to enhance their running performance.

The ESR foot does not suffer from tiredness or fatigue, once the energy is stored in the system it can slowly be recovered during latter stages of the running when the sound limb begins to get tired. A bi-lateral amputee running at steady state needs to create constant input or supply of energy or force equal or slightly more than the loss in one cycle in order to create a sudo-resonant condition that can become almost self-sustaining. Although this hypothesis was successfully simulated, to conclude this work a mechanical cyclic loading system needs designed to validate this argument and that is the subject of the future investigation.

With further study and subsequent prosthesis design optimisation, it is possible that the performance gap between able-bodied and athletes with a lower-limb amputation will narrow, notably over longer running distances such as the 200m or 400 m, 10 Km or the Marathon.

CONCLUSION

The above simulations shows that depending on the relative magnitude and phase of such cyclic force or energy input to such systems the outcome can be any of the following:

a) It can dampen the motion, if the input energy per cycle by the athlete is less than the losses per cycle in the system or if the shape and phase of the input force is not synchronised with or in right phase with the natural modal characteristics of the system causing the mass to act as additional damper, stopping the motion quickly.
b) It can result in a steady state or harmonic hopping, jumping or running motion. That is if the input energy per cycle and losses per cycle are equal and also if the shape and phase of the input effort is also synchronised with the natural modal characteristics of the system.
c) It can result in higher potential energy and extra gain in height if the magnitude of the input energy is more than the losses in one cycle and also is applied at correct phase and shape.

Therefore if synchronised cyclic/sinusoidal excitation energy or force is applied as right frequency and phase to this system, it can result in a favourable outcome.

It has been shown that at the bottom of the travel (ground strike) when the ESR prosthesis deflection is a maximum the system goes into isolation where the inertia force and stiffness force cancel each other out. So any input or additional energy due to muscle effort, hip action or knee, as long as it is more than the losses due to damping in one cycle, will go into the system un-resisted resulting in extra gain in energy. The differential values of this energy results in one of the three outcomes: damping, steady state or increasing amplitude or height).With further acknowledgement of this phenomenon and subsequent prosthesis design optimisation, it is possible that the performance gap between able-bodied and athletes with a lower-limb amputation will narrow, notably over longer running distances such as the 10Km or the Marathon.

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