

Simulation of gait asymmetry and energy transfer efficiency between unilateral and bilateral amputees

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Abstract Efficient walking or running requires symmetrical gait. Gait symmetry is one of the key factors in efficient human dynamics, kinematics and kinetics. The desire of individuals with a lower-limb amputation to participate in sports has resulted in the development of energy-storing-and-returning (ESR) feet. This paper analyses a case study to show the effect of symmetry and asymmetry as well as energy transfer efficiency during periodic jumping between simulated bilateral and unilateral runners. A custom gait analysis system is developed as part of this project to track the motion of the body of a physically active subject during a set of predefined motions. Stance and aerial times are accurately measured using a high speed camera. Gait frequency, the level of symmetry and the non-uniform displacement between left and right foot and their effects on

the position of the Centre of Mass (CM) were used as criteria to calculate both peak energies and transformation efficiency. Gait asymmetry and discrepancy of energy transfer efficiency between the intact foot and the ESR are observed. It is concluded that unilateral runners require excessive effort to compensate for lack of symmetry as well as asymmetry in energy transfer, causing fatigue which could be a reason why bilateral amputee runners using ESR feet have a superior advantage over unilateral amputees.

Keywords Gait symmetry · Kinetics · Unilateral and bilateral · Image processing

1 Introduction

Paralympic running/sprinting has experienced many technological changes. In competitive parasports, amputee's performance is the most important factor, above other prosthesis design considerations such as comfort and cost. 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 absorbing and returning energy in the same manner as a trampoline. Although ESR has been in service since 1985, there is little theoretical or analytical treatment of the science behind the concept.

The energy efficiency of ESR prostheses can vary. Energy return rates have ranged between 31 % [1] and 95 % [2, 3]. Studies of the biological lower limb have shown that the ankle is able to generate a 241 % energy return [1], making a prosthesis a restorative device with performance falling a long way short of that of a biological limb [4]. In a review of transtibial ESR prosthetic devices

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Hafner et al. [5] noted that lack of power generation is a major barrier in creating gait symmetry. However, there are advantages compared to a normal foot: (a) it does not suffer from fatigue; (b) it has fixed properties/characteristics allowing simple transformation of potential energy to kinetic energy to stored energy and back. This allows the energy to be stored in the body mass and not in the foot.

Limb kinematics in transtibial amputee subjects are similar to those for individuals with sound limbs while kinematics for transfemoral amputees show a large gait asymmetry between contralateral limbs [6]. Physiological function is similar between amputee and intact limb subjects while mechanical function in sprinting differs between these two categories [7]. ESR prostheses allow amputees to reach the same energy cost when running as able-bodied persons [2]. Brüggemann et al. [3] showed that lower inertial properties of a prosthesis result in less mechanical work in lifting and accelerating the legs. Hobar et al. [8] discussed some advantages of ESR such as shorter swing time and longer contact lengths and disadvantages such as lower ground reaction force [9] and higher injury risks.

Until now ESR feet have mostly been prescribed based on their static characteristics and linear static stiffness determined experimentally using idealised boundary conditions. Their dynamic characteristics are poorly understood and the limited literature available shows inadequate understanding of the science behind the vibration or harmonic response of the system. There are few studies of the dynamics characteristics of ESR, as discussed below.

Noroozi et al. [4], studied the dynamic characteristics of Elite Blade composite feet, demonstrating the performance enhancing characteristics of these feet when used by a bilateral amputee in the latter stages of longer distance races such as 200 and 400 m. Vinney et al. [10] showed mathematical/FEA modelling of the ESR foot as means of performing inverse dynamics to be used to pre-set or tune the foot for walking, jogging, running and sprinting. Noroozi et al. [11] showed that modal analysis of the mass and foot system clearly determined the three main parameters in dynamic response: frequency, mode shape and damping. Noroozi et al. [12] also developed the basic theories behind the dynamic elastic response of these feet to cyclic and impulse excitation and also demonstrated their response to impulse synchronisation, which can result in a trampoline effect.

Current technology is not ready to provide perfectly symmetric gait for unilateral amputees. The difference between unilateral and bilateral dynamics when using ESR feet needs to be investigated further to determine participation of amputee athletes on both ethical [13] and physiological considerations [3, 7]. Further concerns have been raised about how this technology will be judged in the

future to ensure ethical inclusion of such technology in disability sports [14]. This is also substantiated by Hassani et al. [15], who showed statistically that bilateral amputee using ESR feet dominated the Paralympic Games post 2008, when these ESR feet were first introduced.

1.1 Symmetry

By definition, asymmetry, or lack of symmetry, appears to be a relevant for differentiating normal from pathological gaits. Gait asymmetry is often described as a ratio of the kinematic or kinetic parameters between the right and left sides [16]. Different parameters have been used to determine gait asymmetry for amputees such as ratio index [17], coefficients of variation [18], correlation coefficients [19], symmetry index [20], variance ratios [21], principal component analysis [22], and root-mean-square difference [23], symmetry angle [24], butterfly plot [25] and autocorrelation coefficient [26]. According to Kaufman et al. [16], most of these tools have major limitations because they do not provide a measurement of the symmetry magnitude. Hence, the asymmetry effect cannot be quantified. This study proposes to use the jumping frequency and gait efficiency associated with displacement of centre of mass (CM) to investigate and quantify the asymmetry effect between the bilateral and unilateral amputees.

1.2 Energy transfer

It is known that energetic costs of locomotion depend largely on body size, gait and speed. For example, previous research has shown that the energetic cost of walking and running increases progressively with the speed of movement [27]. Differences in energetic cost for different gait patterns such as running and walking have been also demonstrated [28, 29]. Energy consumption is commonly measured using heart rate and oxygen consumption, which can be further used in the analysis of the percent MHR (Maximum Heart Rate) and gait efficiency. However, it is difficult with these methods to detect the change due to large variability and therefore only suitable to be used as indicator of overall effort. Hall [30] and Rocha-Vieira [31] showed that the oscillation of the CM on the vertical plane is higher when running compared to walking, leading to a higher energy expenditure. A detailed discussion about the mechanical energy consequences for changes of the CM at different gravity values and walking speeds can be found in Cavagna et al. [32]. CM displacement is proportional to the energy expenditure of the person while jumping according to previous studies. The gait energy transfer efficiency for jumping activities is equal to displacement of CM during the aerial phase (output mechanical energy) divided by CM displacement at stance phase (input stored energy). In this

study, the vertical oscillation of CM is used to evaluate the energy transfer efficiency between the simulated bilateral and unilateral amputees and the penalty in energy consumption needed to overcome the lack of gait symmetry.

Recent studies in this field have failed to propose a better model or improved understanding of the science involved. The effect of various parameters on the overall outcome is still undetermined. Therefore the gaps in the technology needed to achieve symmetric gait in all classes of amputees still exists.

This paper simulates unilateral and bilateral jumping condition to investigate gait symmetry and energy transfer efficiency.

2 Methods

Ethical approval for the study was obtained from the Bournemouth University Research and Knowledge Exchange Office. The participant gave his written informed consent before inclusion in the study.

2.1 Data collection

Experimentally, a series of LED markers were designed and developed by the research team and attached to the individual's leg: two markers on the foot, two between the

ankle and knee, two between the knee and hip joint and one on the *iliac tubercle* as shown in Fig. 1. These markers are designed to emit light and be tracked using a high-speed camera (120 frames per second).

The camera is calibrated in a 2D plane using a custom checkerboard pattern measuring intrinsic and extrinsic camera parameters to compensate for the effect of lens distortion as well as camera translation and rotation. The participant was asked to jump along this 2D calibrated plane. Using a calibrated screen one can measure both absolute and relative displacement and rotation of every element of the leg and the CM. Although the absolute position of the CM is not measured in this study, its vertical displacement is determined from the vertical movement of the *iliac tubercle*.

The test is performed inside a darkened room to compensate for the effects of optical disturbance while processing motion. A custom code in MATLAB (Mathworks, USA) was developed using the image processing toolbox. The code automatically detects links between foot, *tibia* and *femur* and their relative position and angular rotation, while displacement of the marker mounted on the *Iliac crest* is considered as displacement of CM of the person in a 2D plane. The MATLAB code then converts pixel coordinates into units of measurement (mm).

Calibration accuracy is evaluated by performing known motion of markers in different directions in calibrated 2D plane and maximum error of 2 mm was observed.

A custom optical trigger is made using Force Sensing Resistor (FSR) mounted below the individual's shoes. Stance phase is detected while individual's foot touches the ground, when the trigger LED turns ON. The ON trigger LED is recognized in the image processing code and frames with ON trigger LED are recorded as stance phase.

2.2 Subject

One physically active subject (age 29 years; body weight 67 kg) volunteered to participate in the study. The subject was experienced in jumping on a trampoline and was informed of the purpose of the study. The subject gave written informed consent to participate in the study. The subject performed consecutive bouncing jumps alternating left and right legs while keeping his hands interlocked behind his back. He was instructed to reach maximum jumping height similarly in all jumps while keeping the jumping frequency as constant as possible within each test. A number of practice trials were performed before the measured trial.

2.3 Experimental protocol

Three different experiment settings were used.



Fig. 1 Experiment setup

- (a) Jumping up and down along Y axis with both feet contacting the ground (Fig. 2a).
 (b) Jumping up and down along Y axis both feet contacting the small trampoline (Fig. 2b).
 (c) Jumping up and down along the Y axis while one foot contacts the rigid half of trampoline (ground) and the other foot contact the free half of trampoline (Fig. 2c).

Movement of half of the trampoline was constrained by placing a rigid wooden box below one side of it, having the same height of trampoline. In this way one side of the trampoline (below one leg) acts like a rigid floor surface (known as the ground) while the other side (below the other leg) maintain its spring/elastic effect. The box was adjusted to minimise the leg length discrepancy during stance. If one foot bounces on the ground and one on trampoline, it will result in excessive use of energy to compensate for the lack of symmetry in energy consumption. Therefore, the effect of one of the key parameters behind difference in performance between unilateral and bilateral amputees in longer distance races could be investigated.

The developed MATLAB code allowed the markers to be tracked on the image allowing a full kinematic study as well as position, velocity and acceleration monitoring of the individual's leg and CM. The design of this test is informed by the Simulink (Mathworks, USA) simulation of the same setup allowing systematic assessment of the dynamics based on parameters affecting the gait.

For all three experimental settings joint kinematics for both sides are plotted and a symmetric gait pattern is observed between right and left legs. It is also observed that *iliac tubercle* moves only vertically without rotation either forward or backward for both legs. Hence it is assumed the change of CM caused by joint rotation is similar for left and right legs, so the effect of energy

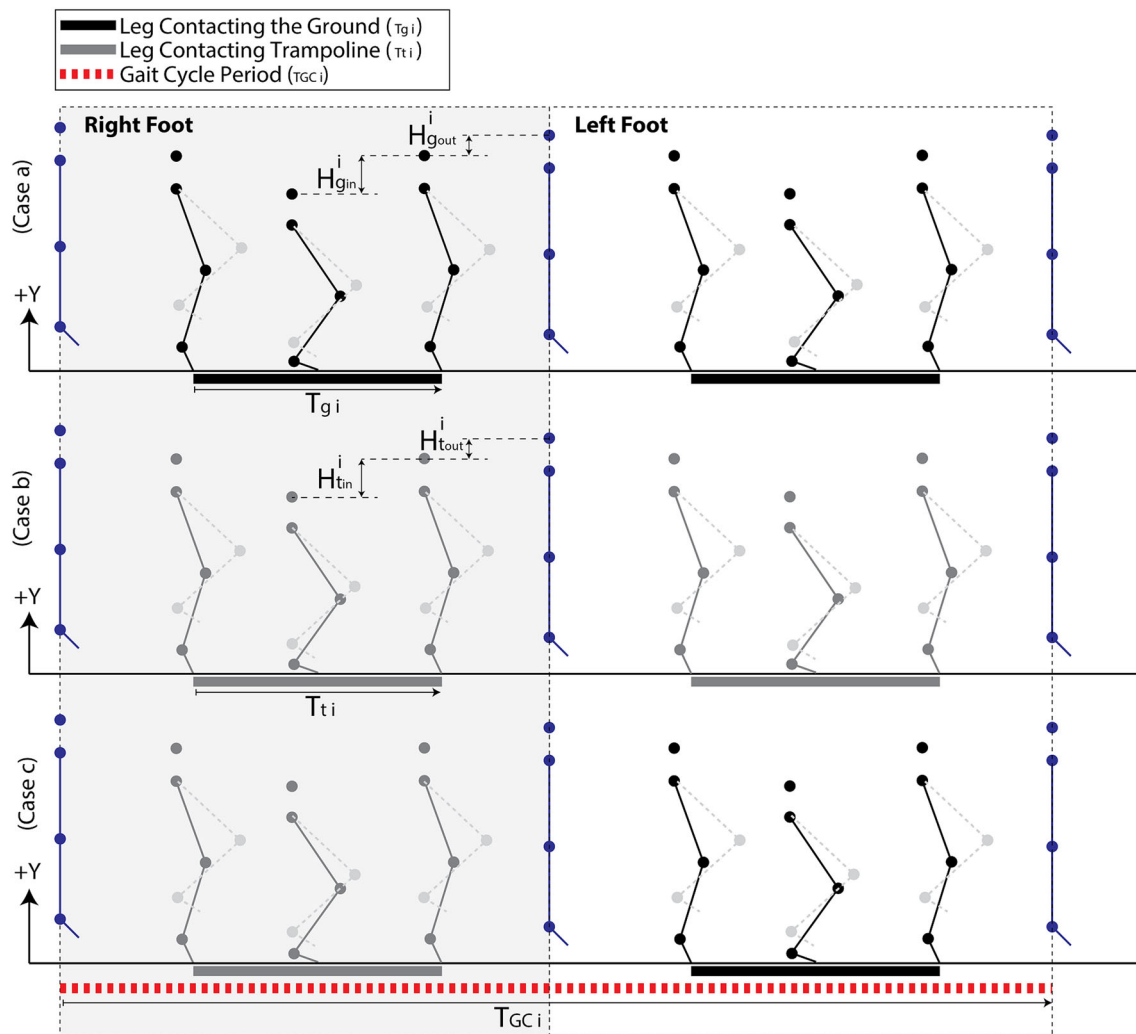


Fig. 2 Test setups. **a** Both feet on ground, **b** both feet on trampoline, **c** one foot on the ground the other on the trampoline

storage and return on CM is compared between right and left.

3 Results

In the first test (Fig. 2a), the test subject jumps up with his right leg touching the ground. When the shoe contacts the ground, trigger LED turns ON and stance phase is automatically detected by image processing code. The moment his right foot leaves the ground (entering flight phase) aerial phase is detected having trigger LED OFF. Aerial phase continues till he reaches his maximum flight height and while going down this time his left foot touches the ground entering stance phase detected by ON trigger LED. Displacement of CM in time and stance and aerial phases are shown in (Fig. 3). Test two (Fig. 2b) was performed following the same sequence as test one, this time with both legs bouncing on the trampoline. Displacement of CM in time, stance, and aerial phases are shown (Fig. 4).

As shown in Table 1 for the case where both feet contact the ground (Case 1) the Jump frequencies ($f_{g1}, f_{g2}, f_{g3}, f_{g4}$) are identical ($f_{average} = 2.52$ Hz). The same observation is found in the case where both feet contact the trampoline (Case 2) where the Jump frequencies ($f_{t1}, f_{t2}, f_{t3}, f_{t4}$) are identical ($f_{average} = 1.95$ Hz) but different from Case 1.

In the third test (Fig. 2c), the individual jumps up with his right foot touching the ground; the moment his right foot leaves the ground contact he enters aerial phase till he reaches his maximum height and while going down this time his left foot bounces on the trampoline in stance phase. Displacement of CM in time and stance and aerial phases are shown (Fig. 5).

As shown in Table 1, the subject found it hard to achieve the same jumping frequency when the average

jump frequency while contacting the free half of trampoline, $\frac{f_{t1}+f_{t2}}{2} = 1.94$ Hz was not identical to the average jump frequency while contacting the ground (rigid side of trampoline), $\frac{f_{g1}+f_{g2}}{2} = 2.43$ Hz. Therefore the person requires additional effort to achieve the desired constant jumping frequency between right and left legs.

The results indicated that an able-bodied person and bilateral amputee require minimum effort to keep jumping frequency constant (i.e., the case where both feet contacting the ground/trampoline) compare to the unilateral amputee (i.e., the case where one foot contacting the ground and another foot contacting the trampoline).

In addition, as shown in (Fig. 5) it is discovered that the gait cycle has the same period for all the cases ($T_{GC1} = T_{GC2}$). Gait cycle describes the interval time/period where the same foot contacting to the ground before flight phase and contact to the ground during landing stage.

3.1 Energy transfer efficiency

The symmetry between right and left in jumping is found for the first two cases (Fig. 3) and (Fig. 4) where the CM displacements are almost constant while jump asymmetry occurs in the third case (Fig. 5) where CM displacements differ between the right and left foot. It may need further explanation to relate jump asymmetry and the CM displacement. So far, from the literature, CM displacement has been associated with energy expenditure/energy consumption rate but not gait asymmetry.

In jumping, elastic energy can be stored (during stance phase) in the muscle–tendon complex (or an ESR prosthesis) and it is released as mechanical work (during aerial phase). In this study spring effect of ESR is modelled using a trampoline.

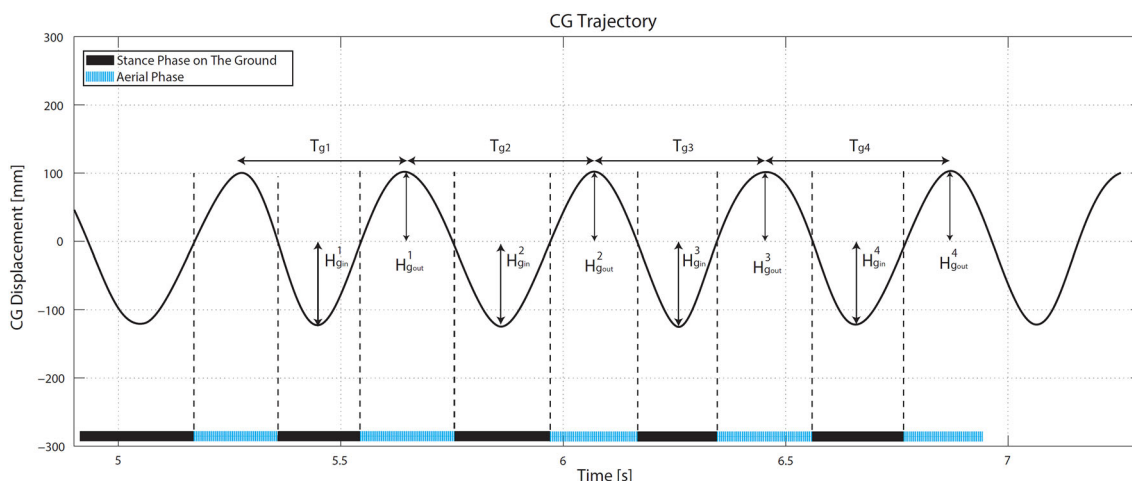


Fig. 3 Feet contacting the ground alternately

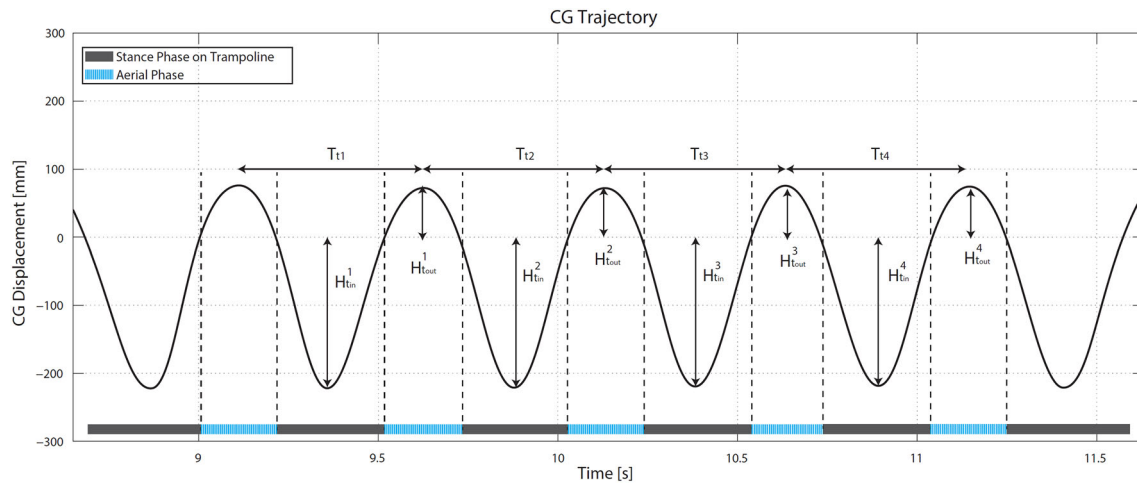


Fig. 4 Feet contacting the trampoline alternately

Table 1 Jumping frequency and energy transfer efficiency

Case number	1	2	3
Average jumping frequency	2.52 Hz	1.95 Hz	1.94 Hz/2.43 Hz
Average energy transfer efficiency	83 %	36 %	38 %/72 %

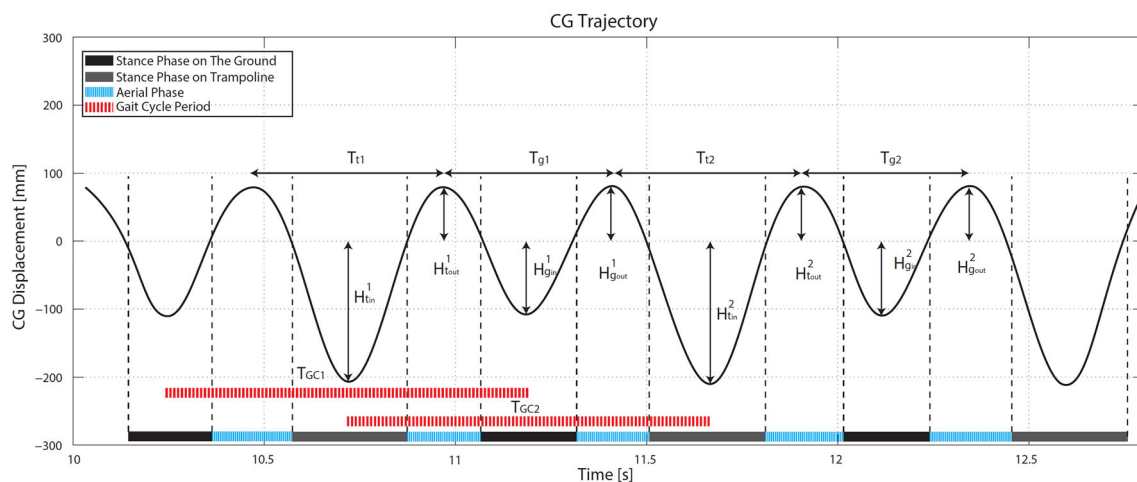


Fig. 5 One foot contacting the free half of trampoline and the other foot the constrained half

It is assumed that the CM displacement is proportional to the energy expenditure of the person when jumping according to previous studies [30–32]. Let the H_{gin}^i be the effective CM displacement that represents the input energy used by foot of a person touching the ground to achieve a certain height, and H_{tin}^i to be effective CM displacement that represents the input energy used by foot of a person touching trampoline to achieve a certain height.

Energy transfer efficiency is defined as the ratio of stored elastic energy in muscle–tendon complex or ESR (represented by CM displacement during stance phase) to mechanical work represented by height of following jump

[33]. The energy return rate is evaluated as an aspect of energy consumption [34]. We can measure the energy output in term of CM displacement.

Depending on whether the foot is hitting the ground or trampoline, the jump energy transfer efficiency for i th cycle, η_g^i or η_t^i , can be found from:

$$\eta_g^i = \frac{H_{gout}^i}{H_{gin}^i}, \eta_t^i = \frac{H_{tout}^i}{H_{tin}^i}$$

where H_{gout}^i and H_{tout}^i are CM displacement at aerial phase (released mechanical work), H_{gin}^i and H_{tin}^i are CM displacement at stance phase (stored energy in muscle–tendon

complex or ESR), and g and t indicate the ground and trampoline cases, respectively.

As shown in Table 1 in the first case average energy transfer efficiency is 83 % while in the second case, efficiency decreases to 36 %. This reduction in energy return efficiency could be explained by the fact that a normal leg having functioning ankle joint is able to generate up to 241 % energy return [1] while a leg using ESR (In this case trampoline) behaves as a mass (body weight) spring (ESR/trampoline) system to return stored energy and not generating any additional work.

In the third case one leg (contacting trampoline) experiences an average energy transfer efficiency of 38 % while the other leg (touching the ground) has average energy transfer efficiency of 72 % meaning in this case the subject needs to introduce excessive effort to compensate for asymmetry of jump efficiency between legs.

These results show that if both legs touch the ground, stored energy in the muscle–tendon complex and generated work by the ankle could produce greater mechanical work in comparison to the scenario which both legs experience the trampoline contact condition. It is also thought that if one leg contacts the ground while the other one contacts the trampoline, that the energy transfer efficiency between right and left leg will fluctuate which requires excessive compensation effort.

In this experiment a trampoline is used to simulate the ESR spring effect and it is concluded that unilateral runners require excessive effort to compensate for lack of symmetry as well as asymmetry in energy transfer, causing fatigue. Although trampoline and ESR have different dynamic elastic responses to impulse, both of them act as linear mass spring systems with fixed response characteristics which show limited range of output responses to variety of different inputs in different scenarios of motion.

4 Conclusions

An active ankle can both generate and return a large amount of mechanical energy (work) in a healthy leg, while the ESR foot, used by a below-knee amputee, can only store and return energy that is less than or at best equal to the potential energy stored in the body. The fixed nature of the mechanical characteristics of ESR feet causes limited output responses to a wide range of inputs. In a unilateral amputee this results in an unsymmetric gait which affects the gait efficiency compared to a healthy person or a bilateral amputee with symmetric gait. The dissimilar gait associated with different energy return between right and left in unilateral amputees is usually due to the excessive compensation needed in every step to control the divergence of the CM.

An ESR foot and mass system, resembling a linear mass spring one, generally has fixed response characteristics in terms of natural frequencies and their dynamic elastic response to an impulse, which is a function of both the initial condition and energy input into the system that can be stored in the mass using muscle power while running. Therefore for a given energy state or to maintain a steady energy state, muscle power needs to be applied at current amplitude and phase to store and return energy to the mass while the foot is in contact with the ground. The able foot, not being elastic, can generate different energy transfer efficiencies that can match that of the ESR foot but not vice versa. Hence a unilateral amputee must compensate for the lack of symmetry and try to match the prosthetic limb's elastic response in every step. This can result in additional energy consumption and fatigue in the healthy leg and other limbs over longer distance running (over 100 m), which can result in an unfair advantage of a bilateral amputee over a unilateral amputee.

A bilateral amputee wearing two similar ESR feet can have a symmetric gait. That in turn results in better energy return efficiency. The stored energy in a symmetric gait can later be recovered from the mass and help to sustain the momentum with little extra effort or be converted into higher velocity or more height allowing a large impulse.

In this paper the fixed characteristics of ESR feet are simulated by using a trampoline with fixed static and dynamic characteristics. Three different tests were conducted and it was found that in case of a simulated unilateral amputee maintaining symmetry was the main issue. Therefore it can be demonstrated that an able-bodied participant and a bilateral amputee can bounce symmetrically in jumping activity.

Technology is not yet ready to create a perfectly symmetric gait in unilateral amputees due to the long response time for sensing and the real-time stiffness adjustment system that are needed. The difference between the dynamics of unilateral and bilateral amputees when using ESR feet needs to be further investigated to help with fair classification of amputee athletes.

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