An investigation of the effect of boundary conditions on the mechanical characteristics of an energy storing and returning prosthetic foot subject to non-destructive testing

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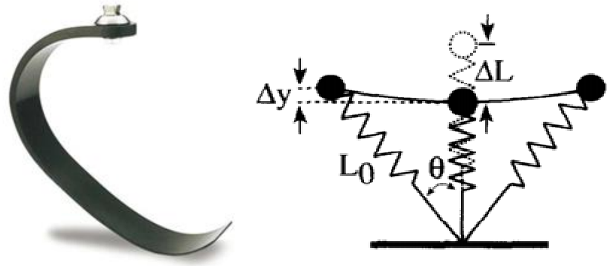
Abstract

It has been recognised that that the mechanical characteristics of Energy Storing and Returning (ESR) prosthetic running feet are not well understood and inconsistent static rating results have been reported elsewhere. The hypothesis that the inconsistent results are due to the varying foot mounting methods used during non-destructive testing was investigated. An ESR prosthetic running foot was rigidly mounted to the load cell of a hydraulic test machine while the metatarsal region of the foot contacted the machine bed. The friction between the foot and the machine bed was varied to create different mounting conditions. For each mounting condition, the foot was displaced vertically and force-displacement data was collected to compare the measured peak force and efficiency of the foot. It is shown that the mounting method affects both the peak measured force (1.2-2.83kN) and efficiency (71-97%) of the foot under test. A novel mounting strategy was then proposed and assessed to overcome the limitations of the previously used mounting methods. The new mounting method produced a linear spring rate across the entire displacement leading to an efficiency of 99.4% and peak measured force of 1.71kN which was in agreement with previously collected data during amputee running. It is concluded that the inconsistencies in reported mechanical characteristics of Energy Storing and Returning prosthetic feet are due to the varying foot mounting methods used during non-destructive testing. A novel foot mounting method has been shown to overcome the limitations of the previous research. Further investigation is needed to fully understand the effect of the prostheses mechanical properties on running performance.

1. Introduction

Recent designs of lower-limb energy-storing-and-retuning (ESR) prostheses have helped individuals run by providing spring-like properties in their amputated leg [(1)]. Of particular importance is the weight of the prosthesis where increased weight may affect speed [(2)]. Running-specific models such as the carbon fibre Ossur Flex Run (Figure 1a) have allowed performance approaching that of the highest level able-bodied athletes while minimising weight.



(a) (b)

Figure 1. (a) Typical ESR running-specific foot (Ossur Flex Run), and (b) Typical spring-mass system used to represent human running [3], where *L* is the Spring length, L_0 is the original effective spring length, and *y* is the vertical displacement of mass

The action of a runner has long been compared with a spring-mass system and has been shown to accurately predict running mechanics [4,5,6,7]. A graphical representation of this concept is shown in Figure 1b. The change in spring length represents the amplitude of compression of the effective leg spring and the change in *y* value demonstrates the vertical oscillation of the centre of mass of the runner. It has been concluded that the spring-mass modelling approach could be applied in the evaluation and design of prosthetic limbs for running and can identify differences in lower inter-limb symmetry when prosthetic stiffness categories are altered [8]. It has been more recently noted that better understanding of the spring-like behaviour and stiffness regulation using ESR feet could optimise their design and improve performance [1]. It was also further stated, as a quest for the optimal prosthetic properties, the need know to what extent the behaviour of the prosthetic leg is dominated by the stiffness [9]. These conclusions suggest the mechanical characteristics of the ESR foot are an important factor in the performance of the amputee.

Despite the importance of the mechanical characteristics being recognised, research reported to date has produced inconsistent results regarding the static rating of ESR feet during non-destructive testing [10-18]. Throughout these works particular attention was paid to the mechanical efficiency of the ESR prosthetic foot on test, but data generated varied dramatically. For example, energy return rates for a composite ESR running foot are quoted as ranging from 100% [19] to 63% [11] for the same model of foot (an Ossur Cheetah). The wide discrepancies in these results would suggest either some degree of measurement error or inconsistent measurement techniques. It is hypothesised that the difference in foot mounting boundary conditions methodologies has produced this disparity in results. If a reliable understanding of the dynamic action of a foot is to be fully understood, these static rating methods should first be interrogated and testing repeated in a reliable and robust manner.

This paper reports on the research undertaken to investigate the effect of changes in mounting boundary condition on the mechanical characteristics of an ESR prosthetic foot during non-destructive testing and proposes a novel foot mounting method to overcome the limitations of the previously proposed methodologies. A standardised foot mounting method will have significant benefits to the research community enabling the performance of ESR feet to be objectively studied.

2. Current ESR prosthetic foot mounting methods for static testing

As has been discussed in section 1, it is recognised that there is inconsistency in measurement techniques to compare the mechanical characteristics of various ESR prosthetic feet. Previous research has focused on the hysteresis and efficiency of energy return of a variety or ESR feet using a dynamic hydraulic testing machine. The research describes how two Teflon sheets (DuPont, Wilmington, DE) were placed between the table and the foot to minimise friction during foot loading and deformation [(17)]. The resulting hysteresis loops are therefore more likely to have occurred as a result of the friction in the slippage system under load than from the damping properties of the spring itself. Such a technique would also potentially result in the changing boundary condition of the ground contact point as the foot deflects, which is not mentioned. This effect has been discussed elsewhere and it is concluded that an assessment of energy return technology when loaded under dynamic conditions demonstrates changes in mechanical stiffness due to bending and effective blade length variation during motion [(20)]. Other investigations have taken place using similar techniques but none have exactly replicated this same methodology. Repeating such an investigation in an accurate manner would be impractical given that the friction coefficient between the toe and test machine would need to be precisely replicated.

It has been found that 100% of the energy absorbed by Sprint-Flex or Cheetah (Ossur, Reykjavik, Iceland) prosthesis was returned [(19)] which is in direct contradiction to another study which defined the efficiency of the Flex Foot prosthesis as 75% [(17)]. A value of 84% has been proposed for the same model of foot elsewhere [(21)] whereas the behaviour of the feet have provided a hysteresis of less than 10 percent, indicating a high percent of energy return, in another study [(10)]. Only one study measuring the dynamic hysteresis has been found which showed a Cheetah foot to have 63% energy efficiency [(11)]. This lack of parity in measurement techniques is further highlighted by noting that the inconsistency in measurement approaches limits the ability for comparison between studies [(8)].

All of the measurement approaches mentioned previously concern the isolation of a prosthetic device and subsequent analysis using laboratory equipment. The approach taken throughout the majority of this previous work has been to mount the prosthetic foot under test rigidly in a dynamic hydraulic test machine or to a sliding mass and exercise it vertically. The proximal end (shank) of the foot is mounted rigidly to the actuator or mass with the distal end free to slide horizontally on the ground surface of the machine. Usually this interface is aided by incorporating a low-friction material to allow the toe to slide against the ground plane as dictated by the geometry of the foot. Displacement data is collected from a linear transducer and ground force from a load cell located either between the proximal end of the foot and the actuator or under the toe of the foot. A pictorial representation of such a setup is shown in Figure 2.

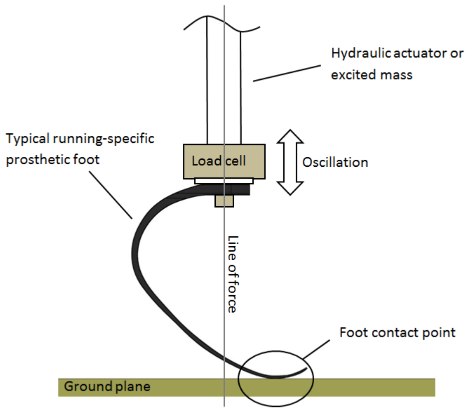


Figure 2. Pictorial representation of ESR foot mounting strategy for previous investigations into static spring rate and efficiency of energy return

If the foot setup (as shown in Figure 2) is examined, it can be seen that the point of ground reaction is not in line with the input force from the actuator (or mass). This offset results in components of the force which can be defined as a function of foot geometry and is manifested as both a vertical and horizontal side load on the actuator. These two components are reacted equally and opposite at the ground contact point. Furthermore as the foot is deflected, the geometry naturally changes (as the foot is progressively loaded)

As the shank of the foot is traditionally limited to purely vertical motion by the actuator and no rotation of mounting is permitted (the shank remains parallel to the ground plane at all times), the geometry of the foot exerts a horizontal force at the toe. This force is reacted by the friction between the toe and the ground plane meaning that longitudinal tension is built up in the foot.

It is clear from examining the mounting methods used previously that the actuator is subjected to side loads and torques as the foot is displaced. Depending on the nature of the foot interface with the ground plane the resulting friction could mean a positive or negative torque at the shank of the foot, or more likely a combination of the two at different amplitudes of deflection. The resulting forces and torques are not likely to be mutually exclusive and each of the factors described will occur with any such foot installation.

Any restriction placed on the foot that reacts against the natural geometrical changes that occur due to displacement (for example friction at the toe) will result in an abnormal shape being forced on the foot. This is particularly apparent if the friction at the toe is greater than the horizontal force, and it is a result of the shank being rigidly attached to the actuator. This abnormal strain being applied to the foot will theoretically, to an extent dependant on the level of friction at the toe, affect the spring rate of the foot. In addition the force required to overcome the friction will affect the spring rate in a manner that will only be apparent on the compression phase of a full cycle. A different level of forcing will be apparent on the rebound phase and this disparity has the potential to significantly affect the recorded hysteresis values (and therefore measured efficiency) of a foot being tested. Quantifying the discrepancies between these mounting methods is the subject of the following investigation in order to justify the need for a new method.

3. Methods

In order to understand the relevance of the ground contact condition, the level of friction between the toe and ground plate should be modified as a variable. It is not yet understood how varying the friction affects the magnitude of the efficiency results and if it can do so by such a large margin as is evident in the literature. This investigation serves to further the understanding of the effectiveness of a rigid shank-actuator mounting mechanism for foot testing and the possible pitfalls of such an approach. A modified mounting method is then assessed and compared with the mounting methods currently used.

3.1 ESR Foot Loading

A previously unused Ossur ‘Flex Run’ Cat6Hi prosthetic running foot was mounted in an Instron 8872 hydraulic test machine (Figure 3a). This was achieved by rigidly attaching the foot with an M12 fixing to the load cell of the machine (attached to the actuator) and allowing the metatarsal region of the foot to contact the ground plane.

In order to define input conditions for the testing, an amputee athlete was observed using an identical Ossur Flex Run foot to that to be tested. The participant was a 32 year old male left-side uni-lateral trans-tibial amputee who was a long-term and regular user of an ESR prosthetic foot who did not suffer from extreme or influential pathologies such as restricted movement or chronic pain that might adversely affect running style or repeatability. They had been using a prosthesis for over ten years following a trauma. The participant had been the user of a category 6Hi Ossur Flex Run for leisure and fitness every day, had retained full joint articulation and suffered from no long-term pain or discomfort. They had a mass of 83kg and as such used the correct stiffness category of foot according to the manufacturer's literature [(22)]. The selection of the participant and testing was conducted following Bournemouth University ethical approval (Reference ID: 4731).

A maximum deflection of 70mm was selected to displace the foot for this testing based on displacement data collected of the amputee during running using a wearable sensor system discussed elsewhere [(23)]. Therefore the foot was displaced 70mm in a series of sine-wave oscillations. An oscillation frequency of 0.5Hz was chosen to simulate a static loading condition and force-displacement data was collected. The foot was subjected to a regime of four full waves and data was averaged to generate a single representative displacement dataset. Force and displacement data was collected from the load cell attached to the Instron test machine and the linear transducer of the actuator. Data was logged using the Instron DAX software (Instron) with a sampling rate of 100Hz.

3.2 Current ESR foot mounting boundary conditions

In order to further understanding of the role of ground friction, the interface of the foot with the ground plane of the machine was modified to vary the friction between the two surfaces for three conditions (Figure 3b-c). These friction conditions are undefined in terms of their coefficient but for the purpose of this investigation they serve to demonstrate the trend of variability of the deflection results for different boundary conditions.

The foot contact conditions used to alter the level of friction between the metatarsal region of the ESR prosthetic foot and the bed plate of the Instron test machine were: Condition 1: Low friction - Bearing rollers were attached to the metatarsal region of the foot to create a virtually friction-free condition (Figure 3b); Condition 2: Medium friction - The carbon fibre surface of the foot was allowed to contact the cast iron bed of the test machine directly. No lubrication was added and the bed was clean and dry (Figure 3c); and Condition 3: High friction - A sheet of ultra-high friction polymer material was placed between the foot and the bed of the machine. This material made slippage of the toe almost impossible when deflected (Figure 3d).

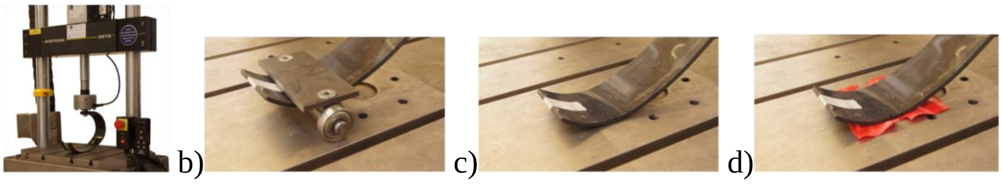
a) 

Figure 3. a) Typical foot setup in the Instron 8872 hydraulic test machine, b) Condition 1: Low friction, c) Condition 2: Medium friction and d) Condition 3: High friction

3.3 Modified MountingFixture

A novel mounting strategy was devised (condition 4) that allowed a single rotational degree of freedom at each end of the prosthetic foot (Figure 4). Instead of the foot being rigidly mounted to the load cell the shank was allowed to rotate about its axis (when viewed in the sagittal plane) on a pair of fulcrums. A steel cradle was designed and fabricated with a clamping bracket that could be attached at any point of the metatarsal region of the foot that not only allowed the same single degree of freedom as the shank on a pair of fulcrums, but also allowed precise definition of the ground contact point.

This arrangement only allows flexibility in the sagittal plane and means that any prosthetic ESR foot of a similar style can be attached or removed without damaging or affecting the structure. To further protect the composite layup and improve safety, the distal end of the foot was cradled in a rapid prototyped (using Fused Deposition Modelling) block that located inside the mild steel framework of the fixture and matched the curved profile of the toe region (Figure 4b). Between the upper and lower surfaces of the foot and the fixture a thin ultra-high friction membrane to prevent slipping was inserted. Therefore, regardless of the amplitude of deflection of the foot the upper and lower interface points are always aligned. No horizontal components of the force can exist and the actuator is only subjected to pure vertical loading conditions. Furthermore because of the rotational degrees of freedom at each end of the foot it is not possible to establish a torque reaction at either of the mounting interfaces.

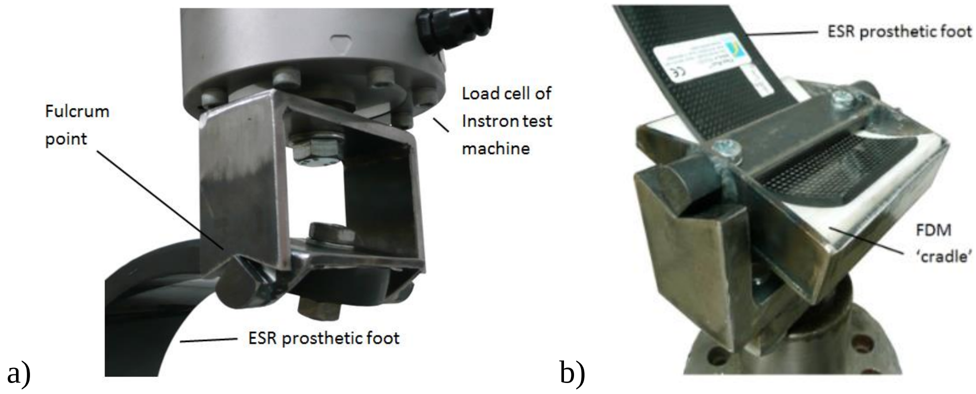


Figure 4. Details of the fabricated brackets that a) clamps to the shank of the foot and provides the upper fulcrum points for attachment to the load cell of the Instron test machine and b) clamps to the metatarsal region of the ESR foot

3.4 Analysis of experimental results

The force - displacement data was averaged for each test condition and a hysteresis curve was generated for each. The efficiency of each test condition was determined by calculating the areas (energy) under the respective curve of the hysteresis graphs using equation 1. This was performed for both the compression and rebound phases of the displacement cycle.

$$\text{Efficiency } (\%) = \frac{\text{Compression Phase Energy}}{\text{Rebound Phase Energy}} \times 100 \quad \text{............................(1)}$$

4. Results

Force – displacement graphs for each test condition can be seen in Figure 5 and Table 1 gives an overview of the performance of the foot for each mounting condition.

As can be seen in Table 1 the efficiency values vary considerably across the test conditions. An interesting additional observation is the reaction force exerted by the foot at maximum deflection. For both of the conditions that involved restriction of the toe (with a friction element included in the setup) the peak force is similar at 2.8kN (Figure 5b and c). However condition 1 was unrestricted and demonstrates a peak force of less than half that of conditions 2 and 3 at 1.2kN (Figure 5a). The reason for this disparity in peak force is the geometry of the test setup. As the foot deflects, the toe region exerts a force in the anterior direction. Condition 1 features rollers to allow the free sliding of the toe region of the foot against the ground plane therefore not allowing any reaction force to act against this anterior force. To compound this effect the geometry of the foot is such that as the foot deflects the rollers move away from the centreline of the actuator. This results in lower amplitude of deflection of the foot for any given amplitude of the actuator.

A further observation is that test conditions 2 and 3 encouraged an exponential spring rate whereas test condition 1 demonstrated a near-linear rate. This is a result of the changing ground contact point of the foot relative to the toe. As was observed during loading, the contact point shifts significantly rearwards (away from the toe) as deflection increases therefore shortening the effective lever arm of the foot and progressively increasing the rate. Condition 1 features a controlled ground contact point in that the rollers are in a fixed position on the foot. The effective lever arm of the foot therefore remains static and results in a near-linear spring rate.

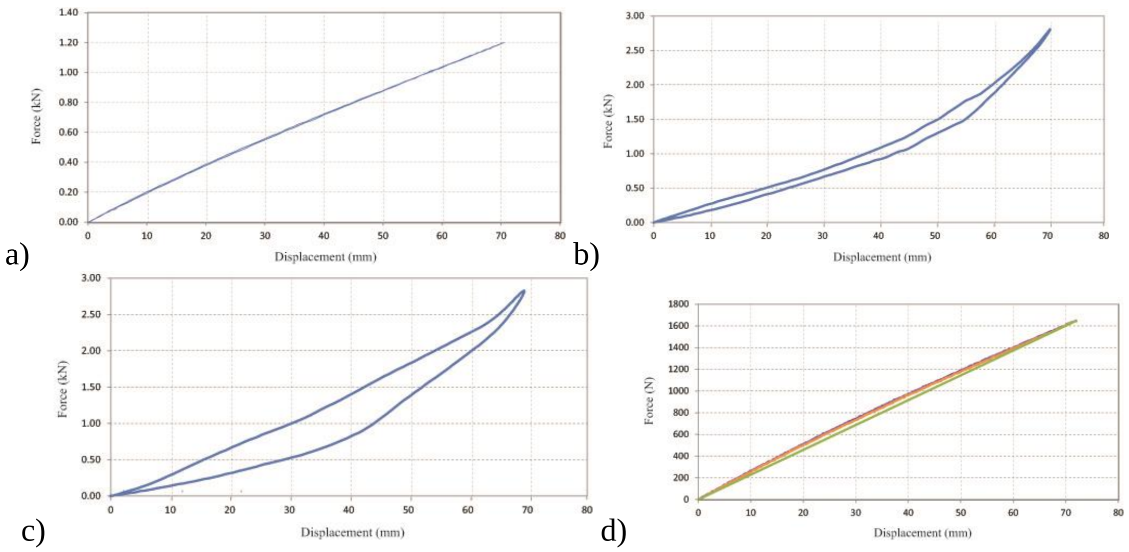


Figure 5. Hysteresis curve of mounting a) condition 1, b) condition 2, c) condition 3 and d) condition 4

Table 1. Peak force and efficiency measure from the ESR under each mounting boundary condition for all foot mounting conditions demonstrating the change in both peak force and efficiency (energy return) despite identical input conditions

	Peak Force (kN)	Efficiency (%)
Condition 1	1.2	97
Condition 2	2.81	86
Condition 3	2.83	71
Condition 4	1.71	99

This investigation has shown that mounting the foot in a variety of ways can change the apparent efficiency of the device. Despite identical input conditions the disparity in results is significant. There is a variation in efficiency of 28% and in reaction force of over 1.6kN by purely changing the interface condition of the toe with the ground plane of the test machine. It is clear that if the ground contact condition is not controlled, the accuracy of data obtained from the foot when undergoing tests of this nature can be brought into question. If the toe is required to slide against the ground plane, any element of friction will introduce a value of hysteresis. It is important to note that the inefficiency measured throughout this investigation is as a result of energy dissipated at the toe interface, not as a result of the characteristics of the foot itself. When rollers were introduced, effectively eliminating friction at the toe in condition 1, the efficiency of the foot was measured at over 97%.

For condition 4, the compression and rebound phase are almost indistinguishable with an energy return efficiency of 99.4% (Figure 5d). The foot returned an almost entirely linear spring rate across the entire displacement. A straight line was superimposed over the compression and rebound curves and at its maximum point the deviation is 5.8% (800N of straight line vs. 851N of compression phase). It was observed that the force reacted by the foot at maximum displacement is 1.7kN. This peak force was the same as that observed from force measurements collected previously while the amputee ran on the same foot [(23)]. This validates the result obtained from the new mounting method as being a true measure of the foot stiffness under similar conditions to that of amputee running.

Condition 1 used rollers to virtually eliminate friction with the ground plane and offers figures closest to condition 4 in terms of efficiency but the peak force exhibited is over 500N adrift. This can be accounted for if the geometry of the test is examined. As deflection increases in mounting condition 1, the horizontal component of the force increases and the vertical component in turn will decrease. The new mounting condition (Figure 4) avoids this by ensuring the interfacing points (at the shank and at the toe) always remain aligned with the force. Therefore the geometry of the force cannot change.

5. Discussion

The results demonstrate the importance of controlling the boundary conditions during testing of prosthetic feet. All of the mounting conditions tested used identical inputs but both the peak forces and values of foot efficiency measured varied significantly.

Previous research that addresses the efficiency of energy return from ESR prosthetic feet is conducted with the shank of the foot rigidly attached to either the actuator of a test machine or to a mass that is restricted in the vertical plane. In doing this, as the amplitude of displacement increases and the foot is progressively deflected, the test geometry changes. The shape of the foot is influenced and according to the toe interface with the ground plate of the test machine a horizontal force and torque is exerted on the actuator or mass. The discrepancies of historical test results from authors can therefore be explained and a new and novel mounting method is defined.

Mounting the foot on fulcrum points at both the proximal and distal ends (at the shank and at the toe) means that the geometry of testing remains unchanged throughout the displacement cycle. The effective ground contact point remains the same both relative to the toe of the foot and also to the ground plane and results in an almost entirely linear spring rate. This is contrary to previous work [(17,20)] which used a similar test with the distal end of the foot sliding against a low-friction medium.

This testing has shown that the mounting of the foot, even for a simple displacement test, is fundamental to achieving repeatable and reliable results. If a foot were mounted in such a manner as described above on two consecutive days, it is possible that the level of friction will be different (due to contamination, humidity in the air or ambient temperature) and results will not be comparable. Also the ground contact point is undefined and unrealistic when compared with an amputee using the foot for running.

This investigation suggests that if further testing is to be conducted using a rig-mounted foot the following mounting conditions must be satisfied:

- there must be effectively no friction at the mounting interfaces to dissipate energy
- the centreline of the actuator must always align with the ground contact point

It is important to note that this testing was not intended to replicate the action of a runner but instead to characterise the prosthetic device as a standalone component [(24)]. Future research is needed to fully understand the effect of the prostheses mechanical properties on running performance. All of the testing in this research has been carried out in a static condition as the rate of deflection was sufficiently low to represent the foot in a static state. A natural progression for the research is to now characterise the same Ossur foot at higher, more representative rates of deflection. This would provide an understanding of the properties of the foot when being used by an amputee athlete and how, if at all, this differs from the static characteristics.

6. Conclusions

This research has demonstrated the importance of the mounting condition if an ESR prosthetic foot is subjected to non-destructive testing. The peak force, spring rate and efficiency of energy return are all affected by modifying the ground contact condition. It was found that there is a variation in efficiency of 28% and in reaction force of over 1.6kN by purely changing the interface condition of the toe with the ground plane of the test machine. The revised mounting method for the device on test has confirmed that the Ossur Flex Run foot has an energy return efficiency of >99% with a linear spring rate. Assuming that a single ground contact point can be defined, a linear spring rate for the foot can be established using this method to support the hypothesis of a spring – mass system. The principle of comparing amputee running with a spring–mass system is a recurring theme when the associated literature is reviewed. The stiffness of the spring (or in this instance the ESR foot) is fundamental to the frequency response of the system. Establishing a reliable figure of energy input versus return will also advise future research intended to improve the efficiency of amputee running.

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