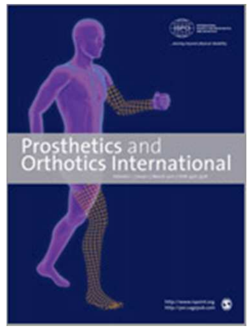

Dynamic characterisation of Össur Flex-Run Prosthetic feet for a more informed prescription

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Dynamic characterisation of Össur Flex-Run Prosthetic feet for a more informed prescription

Abstract

Background: The current method of prescribing composite Energy Storing and Returning (ESR) feet is subjective and is based only on the amputee's static body weight/mass.

Objectives: The aim is to investigate their unique design features through identifying and analysing their dynamic characteristics, utilising modal analysis, to determine their mode shapes, natural damping and natural frequencies. Full understanding of the dynamic characteristics can inform on how to tune a foot to match an amputee's gait and body condition.

Methods: This paper presents the modal analysis results of the full range of Össur Flex-Run running feet that are commercially available (1LO-9LO).

Results: It is shown that both the undamped natural frequency and stiffness increase linearly from the lowest to highest stiffness category of foot. The effect of over-load and under-loading on natural frequencies is also presented. The damping factor for each foot has been experimentally determined and it was found to be ranging between 1.5-2.0%. An analysis of the mode shapes also showed a unique design feature of these feet that is hypothesised to enhance their performance.

Conclusions: A better understanding of the feet dynamic characteristics can help to tune the feet to the user's requirements.

(194 words)

Clinical relevance

This information is needed in order to better predict how the dynamic data can influence the gait pattern and symmetric transition from walking to running. The data is needed to better understand the role dynamic characteristics of the foot plays when prescribing the prosthesis for walking or running.

(48 words)

Keywords: damping, dynamic characteristics, modal analysis, mode shape, natural frequency, prosthesis, energy-storing and returning.

Background

Sport prostheses are used by both upper- and lower-limb amputees while participating in sports and other physical activities. With advances in medicine and an emphasis on maintaining physical fitness, the population of athletes with impairments is growing and receiving great attention [1, 2]. This has revealed a considerable shift in the way our culture considers disabilities over the last few decades [3, 4]. Until the 1980s most prosthetic feet were designed with the main objective of restoring basic walking ability and simple occupational tasks [5]. The need for higher performing feet made has led designers to utilise lightweight and more advanced materials such as Carbon Fibre Reinforced Plastic Composite (CFRP). This has resulted in the development of a new generation of energy-storing-and-returning (ESR) feet, with unique shape and geometrical features. The ESR transforms Potential Energy (PE), into strain energy and returns it back into the body mass in the form of Kinetic Energy (KE) in a short impulses thus helping amputee to accelerate in a forward motion [6]. Their introduction has changed the nature of amputee sprinting sport. ESR feet are now available in many categories, in terms of their stiffness/performance, catering for most types of recreational activity.

The energy efficiency of ESR feet varies between different suppliers. Their energy return rates have been found to range from 31% [7] to as high as 95% [6, 8]. Studies of the biological/intact lower-limb have found that the ankle can generate a 241% energy return [7]. Hence, an ESR foot falls a long way short of replacing the mechanical performance of the biological limb. Closer examination of the dynamics of ESR feet identifies several parameters that are capable of affecting the performance of amputee runners when using these feet. This includes the original shape, the length of the foot, the overall dynamic elastic response to impulse synchronisation and metabolic cost.

By definition the dynamic characteristics of ESR feet are their natural frequency, mode shapes and damping factors [9-11]. Although running with ESR feet is an impulse driven action, the natural frequency of the spring-mass system plays an important role to facilitate the transition from vibration to impulse. Other factors affecting performance of runners using ESR feet could be the excessive metabolic cost, specially due to lack of gait symmetry as observed in unilateral amputees [12]. The effect of each factor needs to be studied individually and their influence on motion can then be better understood.

Over the years, debates of fairness of lower-limb prosthesis running technology in sport were raised [13-15]. To address this issue, research to investigate static and dynamic characteristics of various prosthetic feet have been carried out. Lehmann et al. conducted studies to evaluate the biomechanical and metabolic performance differences between two different prosthetic foot designs [16]. This study used SACH (Solid-Ankle Cushion-Heal) prosthetic feet to test for dynamic elastic response. It was found that the natural frequencies of oscillation for the prosthetic feet were too high to provide energy storage and release that could be synchronised with the kinematic requirements. This finding is not unexpected as the feet used for this test were not designed to store and release a large amount of strain energy such as those made by Össur (Flex-Run) or Blatchford (BladeXT). Noroozi et al. investigated the link between gait symmetry and the effect of dynamic elastic response of the ESR foot to impulse in unilateral and bilateral amputees [17]. Noroozi et al. hypothesised that human input impulse, is needed in order to compensate for loss of energy in one step. This impulse can only assist the motion if it's applied at the right moment and with a force trajectory that closely maps onto the foot. This phenomenon could potentially enhance performance if the foot is used at its optimum dynamic characteristics.

The effect of lack of symmetry due to dissimilar stiffness's on energy transfer rate was investigated by Aslani et al. [12]. It was demonstrated that energy consumption due to lack of gait symmetry is higher than that in symmetric gait and will cause severe fatigue over longer running durations, such as in 200 or 400 metre sprints. It can be shown that an able-bodied individual having a symmetric gait uses less energy than a unilateral amputee when walking [18-20]. Oudenhoven et al. also indicated that the stiffness of the prosthesis is an important parameter to optimize running performance. With this information, the athletes can regulate the leg stiffness during distance running at their preferred step frequencies [21]. These findings infer running efficiency/improved performance can be gained if the running gait can be made symmetrical. Therefore, knowledge of the dynamic characteristics of such feet is important to assist in developing a symmetrical running gait.

This paper presents the modal analysis results of nine stiffness categories of Össur Flex-Run ESR feet in order to understand their dynamic characteristics (natural frequencies, damping and mode shapes). The effect of over-load and under-loading of the ESR foot on the natural frequencies is also presented.

The findings presented in this paper are of importance as the data is not currently available elsewhere. The data is needed to better understand the role dynamic characteristics of the foot plays when prescribing the prosthesis for walking or running.

Methods

The experimental procedure and methodology used to determine the natural frequencies, mode shapes and damping factor of the Össur feet is discussed in this section.

Össur Flex-Run

The Flex-Run is described as featuring a long toe lever and efficient energy return (https://www.ossur.com/prosthetic-solutions/products/sport-solutions/flex-run). The full length keel/toe lever is designed to match the length of the sound foot to provide improved support to the prosthetic limb during late stance. It is claimed that the users spend equal time on the prosthetic foot and natural limb to provide improved walking dynamics and reduced impact to the sound limb. This could lead to improved walking symmetry and reduced impact to the sound limb. Meanwhile, vertical forces generated at heel contact are stored and translated into a linear motion described as Active Tibia Progression. This action is designed to reduce the need to actively push the body forward using the contralateral foot and also equalizes stride length. The benefit of this could be a more natural gait and reduced walking effort.

The Flex-Run is offered in a range of stiffness values, divided into specified categories and are prescribed according to the mass of the amputee through the stiffness prescription guide from Össur (Table 1). It should be noted, that little or no consideration for the specific ability or desired activity level of the amputee is taken into account in the prescription guide.

Table 1: Flex Run stiffness prescription guide

High to Extreme Impact Level	Weight kg	Weight lbs.
1LO	37-44	81-96
2LO	45-52	97-115
3LO	53-59	116-130
4LO	60-68	131-150
5LO	69-77	151-170
6LO	78-88	171-194
7LO	89-100	195-220
8LO	101-116	221-256
9LO	117-130	257-287

Due to the distinct difference in the stiffness of the feet, they will be distinguished by their rating names assigned by the manufacturer as 1LO-9LO (Figure 1).

Figure 1: Full range of Flex-Run Categories.

Modal Analysis

Modal analysis is a well-established experimental method for identifying modal parameters (frequency, mode shapes and damping) in any static elastic structure/system. The technique used to extract these parameters is called

Experimental Modal Analysis (EMA) [21, 22]. The test structure is artificially excited by using either an impact hammer, or one or more shakers. A force transducer is used to measure the input excitation force to the system while the output response of the system is normally measured by using accelerometers. Input and output vibration signals of several locations of the system are determined to obtain a discrete number of Frequency Response Functions (FRFs). Then, the FRF obtained undergoes curve fitting to extract the modal frequencies, modal damping and residue mode shape of the system [23, 24].

Complete modal analysis investigations were conducted on nine Össur ESR feet. A mass of 53kg was attached to each of the nine feet and a full modal analysis was conducted for every foot-mass system combination. In each case, the masses were secured in such a way that the line of action of the total weight passed through the ground reaction point of the foot creating a balanced/equilibrium condition (Figure 2). The fixings were approximately 120 degrees apart and each had enough slack to ensure the displacements in all three orthogonal directions were not suppressed.

Figure 2: Experimental set-up of free-free modal testing.

A total of 18 discrete locations were selected on each foot to attach the accelerometers (Figure 3). The Impulsive excitation technique was used as the test method throughout the study to determine the elastic and damping properties of the feet [22]. An impact hammer, tri-axial accelerometer, in-house data acquisition system and modal analysis software were used to investigate the dynamic characteristics. The specification of the instrumentation used can be found in Table 2. The input signal was the excitation force from the manual impact hammer whereas the output signal was the response due to impact measured by the accelerometer. A data acquisition (DAQ) system consisting of National Instrument NI-USB-9234 modules controlled by the DASYLab software was used. A manual impact hammer was connected to channel 1 of the National Instrument (NI) dynamic analyzer and a tri-axial accelerometer was connected to channel 2, 3 and 4 respectively. In this experiment, a roving tri-axial accelerometer was used while manual impact hammer was excited at fixed degrees of freedom, i.e., point 13 and 2 in the x-axis and z-axis respectively. The tri-axial accelerometer was roved from point 1 to point 18 measuring the response of the structure in the x, y and z directions and this gave a single-input, single-output (SISO) analysis. A sampling rate of 2048 samples/sec was used, and the vibration signal was collected for 2 seconds, so a total of 4096 samples were recorded for post-processing. The modal analysis software (ME'Scope software) was used to draw the three-dimensional structural model of the test rig in coordinate points where every point was connected by straight lines as shown in Figure 3. The displayed point numbers represented each discrete location as in the actual ESR foot.

Furthermore, the FRF estimations acquired through DASYLab software were post-processed by using Me'Scope software. A polynomial curve fitting method was used in the software to extract the modal parameters. Thus, the mode shape obtained corresponding to each vibration mode was recorded and animated using the wire mesh model drawn. Modal damping, 2σ is approximately equal to the width of the resonance peak at 70.7 % of the FRF peak magnitude value, which is the same as half of the peak magnitude value squared. Hence, 2σ is the width at the half power point of a resonance peak in the unit of rad/s or Hz.

Figure 3: Wire-mesh model of Flex-Run used for modal analysis

Table 2: Detailed instrumentation characteristics

INSTRUMENTS	DESCRIPTION
1LO-9LO Flex-Run feet	Used as test rig to perform modal analysis
PCB Impact Hammer, Model 086C03	Sensitivity: 2.25 mv/N Tip type: medium tip with vinyl cover Hammer mass: 0.16kg Frequency range: 8kHz Amplitude range: ±2200 N peak
PCB ICP Accelerometer, Model 356B18	Sensitivity: 1000mv/g Frequency range: (±5%) 0.5 to 3000 Hz Amplitude range: ±5 g peak
NI USB Dynamics Signal Acquisition Module, Model NI-USB 9234	Number of channels: 4 ADC resolution: 24 bits Type of ADC: Delta sigma (with analog pre-filtering)
DASYLab v10	Sampling rate: 2048 samples/sec Block Size: 4096 Channel 1: Impact hammer Channel 2: Accelerometer x-axis Channel 3: Accelerometer y-axis Channel 4: Accelerometer z-axis Averaging: 5 for static conditions Windowing: Force for excitation signal Exponential for response signal
ME'Scope v6.0	To process collected data from NI-DASYLab To define the structural geometry for frequency response function (FRF) modal Analysis To determine the natural frequencies, damping and animated mode shapes after curve fitting process

Using the damped natural frequency and damping obtained from modal analysis, the undamped natural frequency can be calculated from the damped natural frequency (equation 1).

$$\omega_d = \omega_o \sqrt{(1-\zeta^2)} \quad \text{(eq. 1)}$$

where, ω_d = damped natural frequency (rad/s), ω_o = undamped natural frequency (rad/s) and ζ = damping ratio.

By using the constant mass of 53kg and the undamped natural frequency, the stiffness of each foot can be determined (equation 2).

$$\omega_o = \sqrt{\frac{k}{m}} \quad \text{(eq. 2)}$$

where, k = stiffness (N/m), m = mass (Kg)

Results

Table 3 presents the natural frequencies and damping of 1LO-9LO feet with fixed 53kg mass system. The results show that the system possesses the same natural frequency when excited by knocks in X and Z direction. This implies all excitations in these two directions will always excite this natural. This is close to the natural frequency of the running gait for most athletes which has been shown in previous research to reach 4.31Hz during sprinting [25].

Table 3: Dynamic characteristics of 1LO-9LO feet with fixed 53kg mass

Flex-run	1st Natural Frequency knocked in X-dir (Hz)	Damping (%)	1st Natural Frequency knocked in Z-dir (Hz)	Damping (%)
1LO	3.94	1.55	3.90	1.93

2LO	4.02	1.66	4.04	2.06
3LO	4.13	1.65	4.14	1.54
4LO	4.24	1.61	4.24	1.73
5LO	4.64	1.43	4.64	1.63
6LO	4.87	1.65	4.78	1.88
7LO	5.04	1.77	5.00	1.84
8LO	5.21	1.8	5.22	1.81
9LO	5.29	1.54	5.33	1.69

Table 4 presents the undamped natural frequency and the stiffness of each foot using equations 1 and 2. The results show that both the undamped natural frequency and stiffness of the feet increase from the lowest stiffness category (1LO) to the highest stiffness category (9LO).

Table 4: Dynamic characteristics of 1LO-9LO based on fixed 53kg mass

Flex-run	Damped natural frequency (Hz)	Damping (%)	Undamped natural frequency (Hz)	Stiffness (N/m)
1LO	3.920	1.740	3.921	32161.72
2LO	4.030	1.860	4.031	33993.51
3LO	4.135	1.595	4.136	35784.68
4LO	4.240	1.670	4.241	37626.04
5LO	4.640	1.530	4.641	45058.14
6LO	4.825	1.765	4.826	48726.54
7LO	5.020	1.805	5.021	52745.4
8LO	5.215	1.805	5.216	56922.73
9LO	5.310	1.615	5.311	59011.67

Figure 4 shows that with the stiffness of 1LO-9LO known, and assuming the boundary condition is fixed, natural frequency can be predicted based on different mass or masses to be used on a specific foot due to the linearity of the data.

Figure 4: Plot of a) undamped natural frequency (Hz) and b) Stiffness (N/m) against ESR foot stiffness category.

The results show that by simple adjustment of the stiffness when used with the same body mass, the natural frequency can be controlled. Noroozi et al. described the behaviour of the mass and foot system to be similar to a trampoline [9, 11]. If the frequency of the bouncing action during running matches the natural frequency of the perceived mass/spring system then the mass will vibrate. This cyclic rhythm is a form of energy input into the system that is needed to maintain this steady state cyclic/periodic motion, by replacing the loss of energy in one cycle due to damping.

Damping is an important factor in this study. Damping data is not readily available for ESR feet. The decay rate has been used to predict the drop in amplitude of the vibration per unit time. Using the decay rate makes it possible to calculate the percentage drop in amplitude with respect to time elapsed. The damping characteristic for a given system must be physically measured as it cannot be determined using simulation tools. The damping characteristic of the feet have been experimentally determined and the damping of the first bending mode was found to range between 1.5-2.0%. This low damping reduces the energy dissipation in one cycle and thus less energy input into the system is required to maintain the steady state cyclic motion before take-off from the ground.

These modal test results also show the mode shape that is most relevant or suitable for the running action (Figure 5). The mode shapes of all Flex-Run feet are supplied separately as Supplemental Digital Content. It was noticed during this investigation that the Flex-Run tested possessed a unique geometrical characteristic that initiates or promotes a natural and perpetual forward leaping response when excited as its natural frequency. The recoil motion during bounce gave the system a perpetual forwards motion even without any forward excitation force. This important phenomenon, known as Active Tibia Progression by Össur, could reduce the need to actively push the body forward to have a more natural gait and also reduces the walking effort. Without further testing it can only be hypothesised that this could be due to the special geometrical features of these Össur feet, where energy could be stored in the foot in one direction and released naturally in a different direction that is usually aligned with the direction of the run. In a bilateral amputee this can have another significant effect, which is steady-state symmetric beat frequency that can enhance performance over longer distance runs. Further study of this phenomenon will be the subject of future publications.

Figure 5: First bending mode of 1LO at 3.94Hz and 3.90Hz with free-free boundary condition knocked in X&Z-direction respectively

Discussion

Although modal analysis is a powerful tool it is highly sensitive to the influence of other parameters such as changes in boundary conditions that can affect the dynamic response to excitation. This is a very important issue as in a free-free modal testing, the change of boundary condition during modal testing changes due to foot flexure and alignment which will result in discrepancies in the dynamic characteristics obtained. This also implies that using these feet with anything other than strings to hold them in position, such as dedicated test rigs will result in modal data that are not representation of the foot and mass system in isolation. That is because dissimilar material rigs with much higher stiffness will substantially change the boundary condition and the results will show the natural frequencies of the test rig instead of the foot and mass system.

This paper indirectly demonstrates the dynamic flexibility of CFRP composite materials for application in advanced dynamic systems. Specific detail regarding the individual constituents of the material and its construction are unknown. However, the composite laminates used to manufacture running specific feet are all unidirectional and woven carbon pre-impregnated epoxy. The laminate lay ups are non-symmetric and uses a specific laminate lay up for each foot category. Laminates are autoclaved cured and then machined to size.

Conclusion

Nine Össur Flex-Run feet, constituting the full range of feet that are commercially available (i.e. 1LO-9LO), were investigated and the dynamic characteristic results are presented. Currently no such data is available regarding these feet and the influence of mass, stiffness and natural frequency is not properly understood.

This paper presents the damping, mode shapes and natural frequencies of all of these feet. This information will be needed in order to better predict how the dynamic data can influence the gait pattern and symmetric transition from walking to running. From the first bending mode shape, it was noticed during this investigation that the Flex-Run possessed a unique geometrical characteristic that initiates or promotes a natural and perpetual forward leaping response without any forward excitation force when excited as its natural frequency. Further study of this phenomenon is warranted.

Acknowledgements

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Author contribution

All authors contributed equally in the preparation of this manuscript

Declaration of conflicting interests

The authors declare that there is no conflict of interest.

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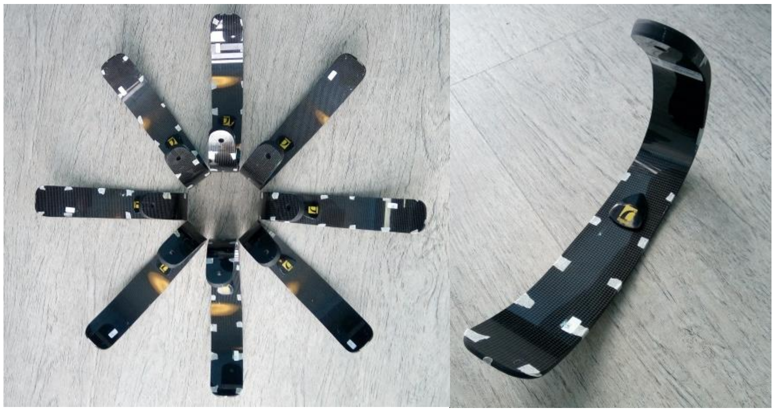

Figure 1: Full range of Flex-Run^{TM}

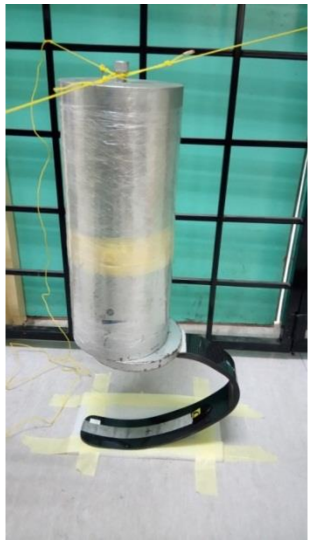

Figure 2: Experimental set-up of free-free modal testing

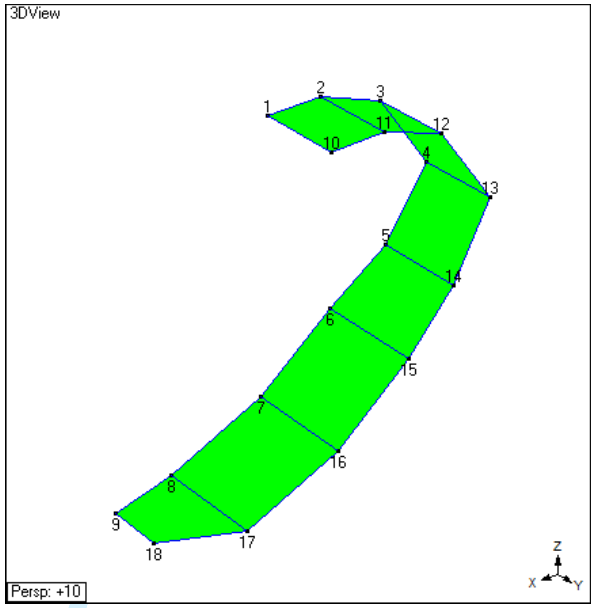

Figure 3: Wire-mesh model of Flex-Run^{TM} used for modal analysis

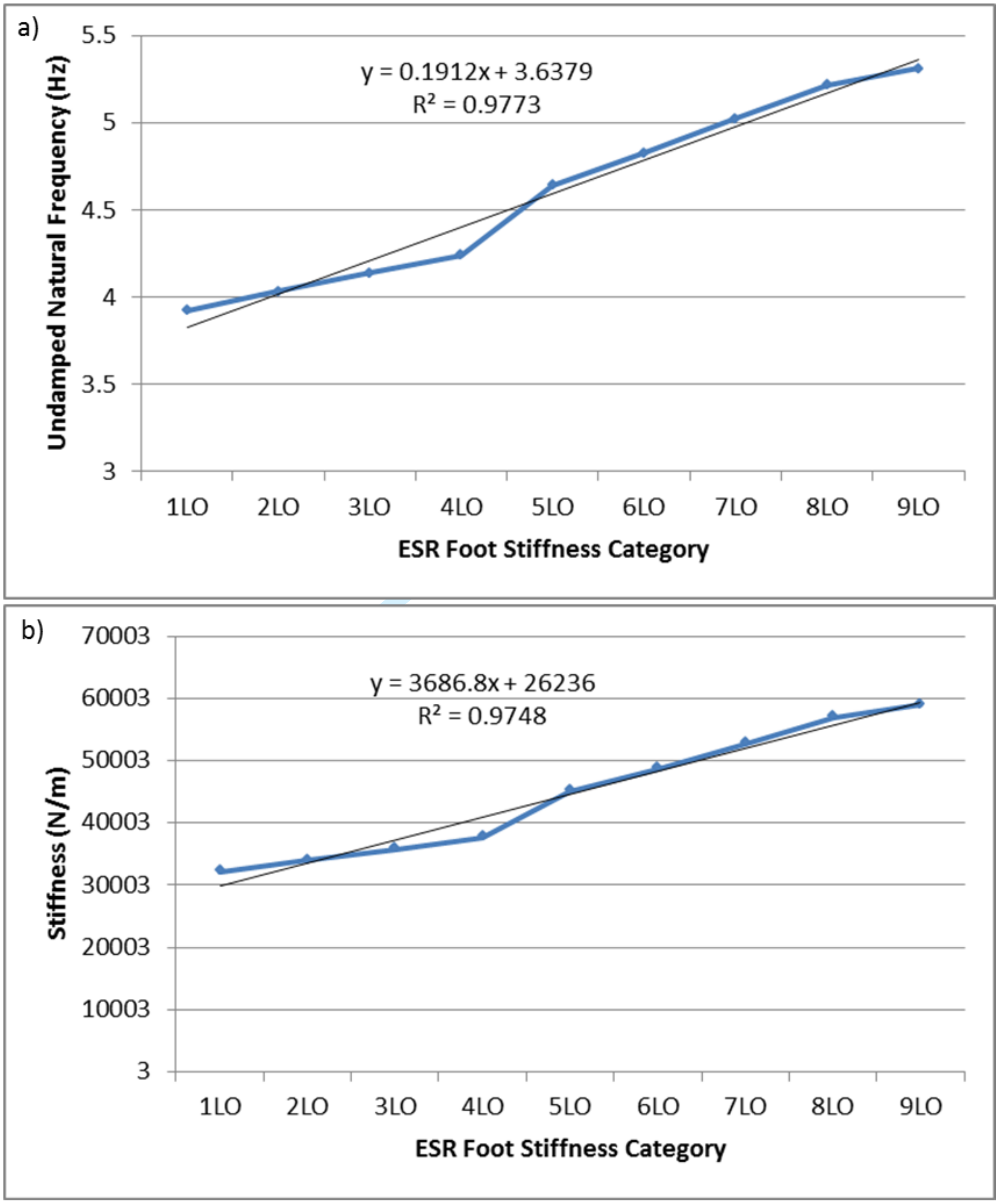

Figure 4: Plot of a) undamped natural frequency (Hz) and b) Stiffness (N/m) against ESR foot stiffness category.

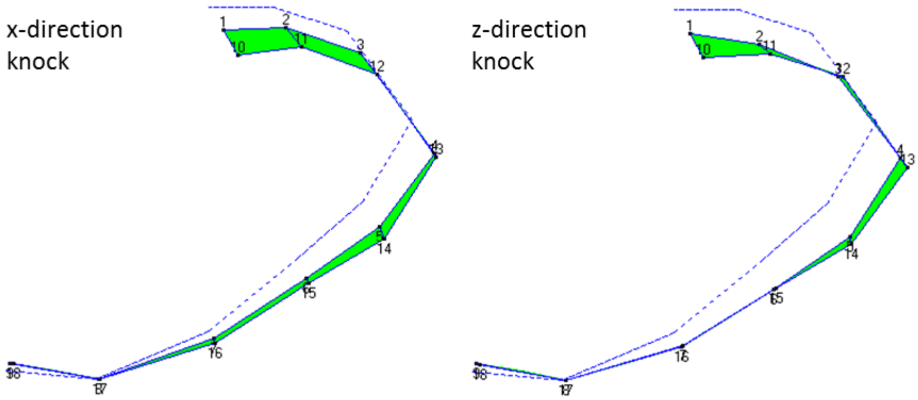

Figure 5: First bending mode of 1LO at 3.94Hz and 3.90Hz with free-free boundary condition knocked in X&Z-direction respectively

Table 1: Flex-Run^{TM} Category Selection Chart

High to Extreme Impact Level	Weight kg	Weight lbs.
1LO	37-44	81-96
2LO	45-52	97-115
3LO	53-59	116-130
4LO	60-68	131-150
5LO	69-77	151-170
6LO	78-88	171-194
7LO	89-100	195-220
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9LO	117-130	257-287

Table 2: Detailed instrumentation characteristics

INSTRUMENTS	DESCRIPTION
1LO-9LO Flex-Run feet	Used as test rig to perform modal analysis
PCB Impact Hammer, Model 086C03	Sensitivity: 2.25 mv/N Tip type: medium tip with vinyl cover Hammer mass: 0.16kg Frequency range: 8kHz Amplitude range: ±2200 N peak
PCB ICP Accelerometer, Model 356B18	Sensitivity: 1000mv/g Frequency range: (±5%) 0.5 to 3000 Hz Amplitude range: ±5 g peak
NI USB Dynamics Signal Acquisition Module, Model NI-USB 9234	Number of channels: 4 ADC resolution: 24 bits Type of ADC: Delta sigma (with analog pre-filtering)
DASYLab v10	Sampling rate: 2048 samples/sec Block Size: 4096 Channel 1: Impact hammer Channel 2: Accelerometer x-axis Channel 3: Accelerometer y-axis Channel 4: Accelerometer z-axis Averaging: 5 for static conditions Windowing: Force for excitation signal Exponential for response signal
ME'Scope v6.0	To process collected data from NI-DASYLab To define the structural geometry for frequency response function (FRF) modal Analysis To determine the natural frequencies, damping and animated mode shapes after curve fitting process

Table 3: Dynamic characteristics of 1LO-9LO feet with fixed 53kg mass

	1st Natural Frequency knocked in X-dir.	Damping (%)	1st Natural Frequency knocked in Z-dir.	Damping (%)
1LO	3.94	1.55	3.90	1.93
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3LO	4.13	1.65	4.14	1.54
4LO	4.24	1.61	4.24	1.73
5LO	4.64	1.43	4.64	1.63
6LO	4.87	1.65	4.78	1.88
7LO	5.04	1.77	5.00	1.84
8LO	5.21	1.8	5.22	1.81
9LO	5.29	1.54	5.33	1.69

Table 4: Dynamic characteristics of 1LO-9LO based on fixed 53kg mass

Flex-run	Damped natural frequency	Damping (%)	Undamped natural frequency	Stiffness
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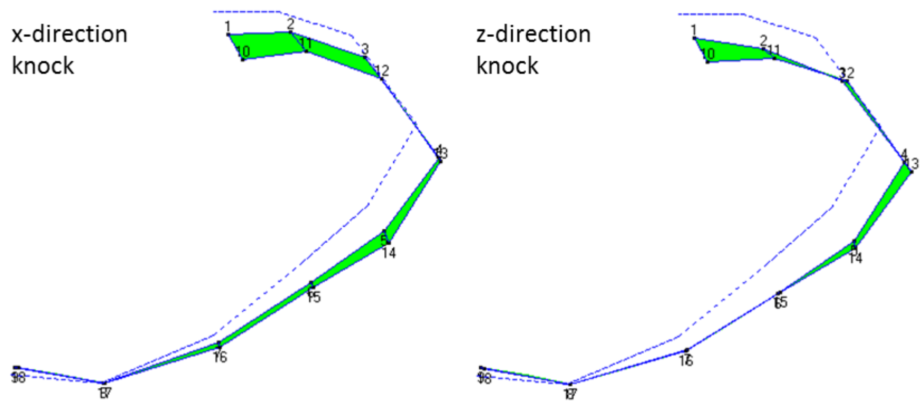

Figure S1: First bending mode of 1LO at 3.94Hz and 3.90Hz with free-free boundary condition knocked in X&Z-direction respectively

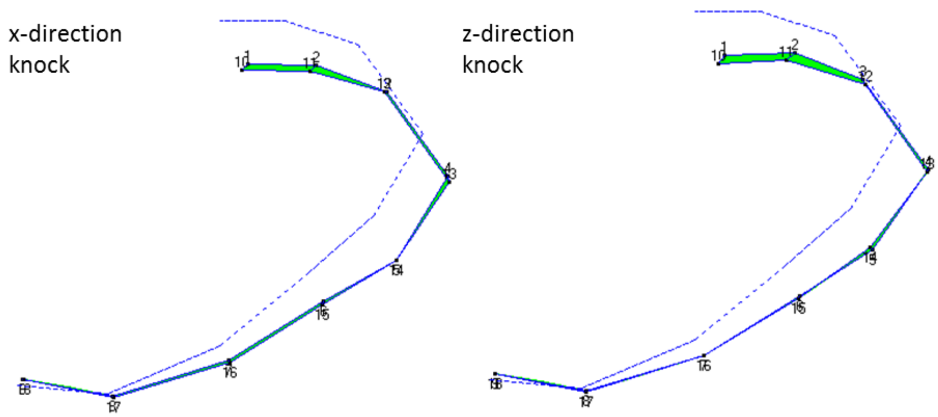

Figure S2: First bending mode of 2LO at 4.02Hz and 4.04Hz with free-free boundary condition knocked in X and Z-direction respectively

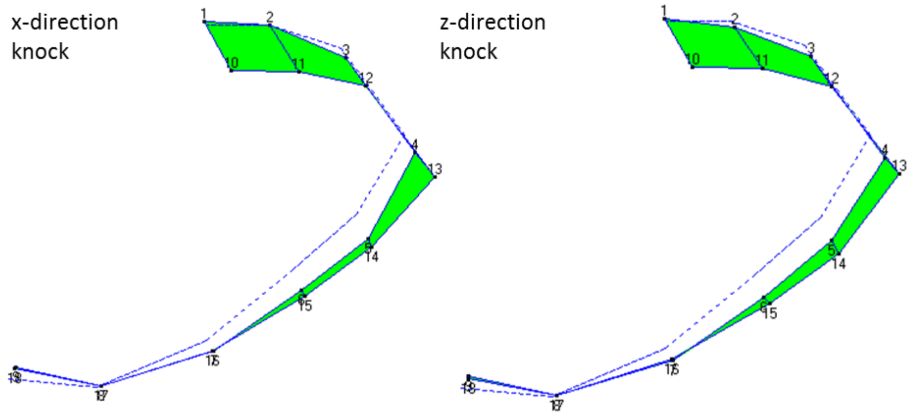

Figure S3: First bending mode of 3LO at 4.13Hz and 4.14Hz with free-free boundary condition knocked in X and Z-direction respectively

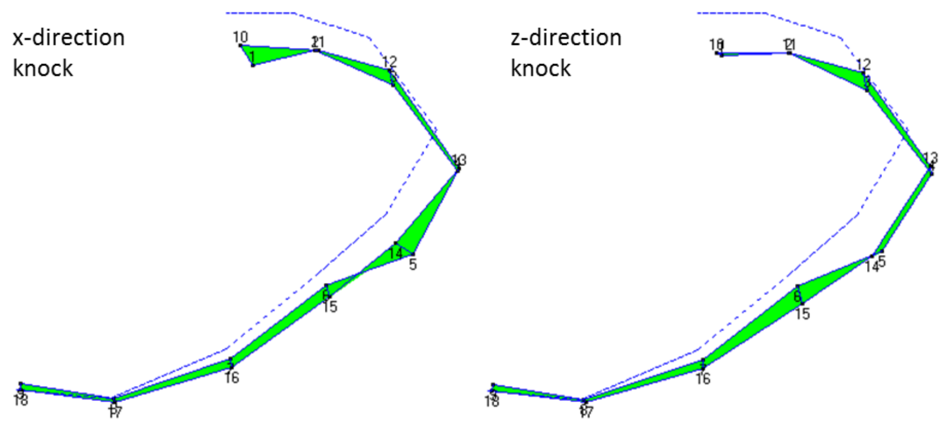

Figure S4: First bending mode of 4LO at 4.24Hz with free-free boundary condition knocked in X and Z-direction respectively

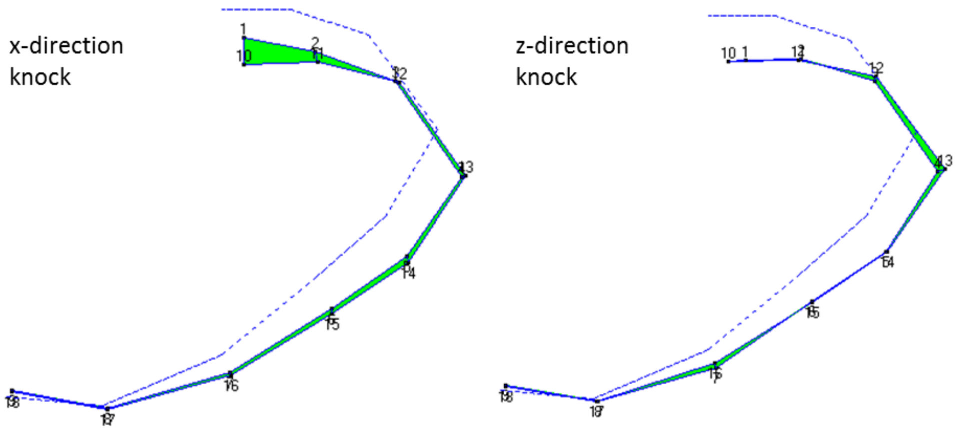

Figure S5: First bending mode of 5LO at 4.64Hz with free-free boundary condition knocked in x and Z-direction respectively

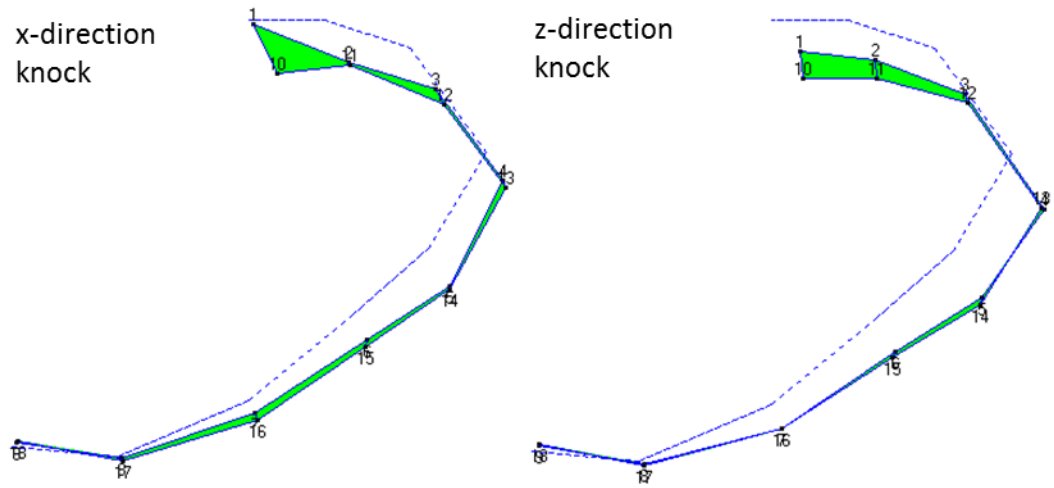

Figure S6: First bending mode of 6LO at 4.87Hz and 4.78Hz with free-free boundary condition knocked in X and Z-direction respectively

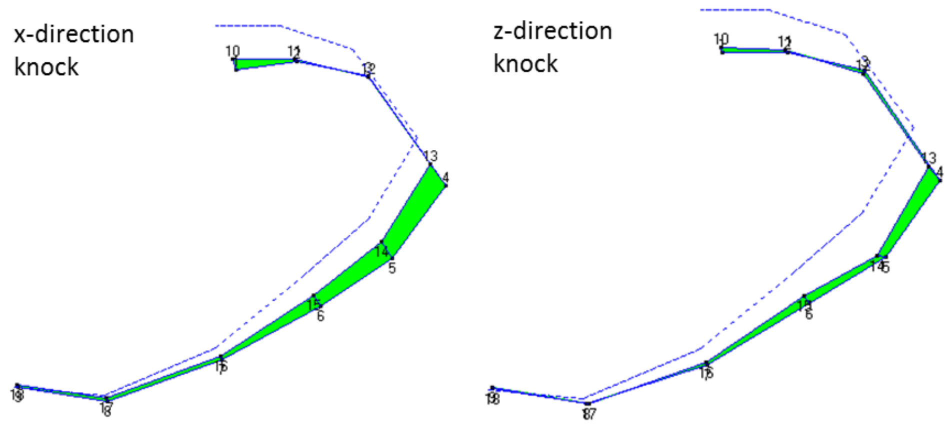

Figure S7: First bending mode of 7LO at 5.04Hz and 5.00Hz with free-free boundary condition knocked in X and Z-direction respectively

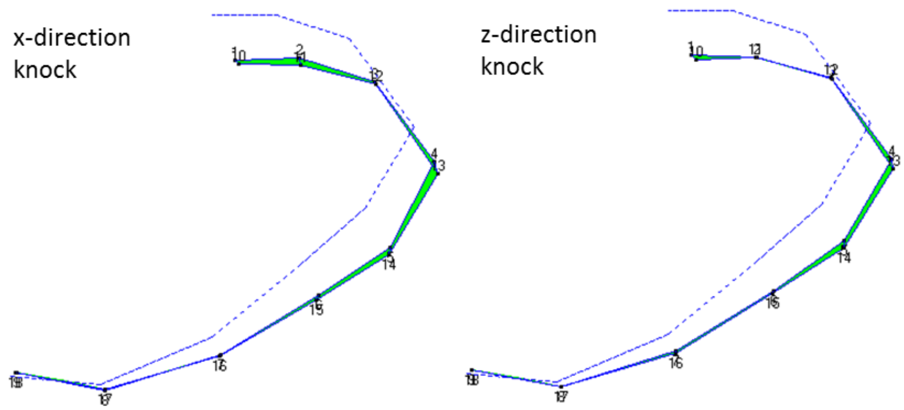

Figure S8: First bending mode of 8LO at 5.21Hz and 5.22Hz with free-free boundary condition knocked in X and Z-direction respectively

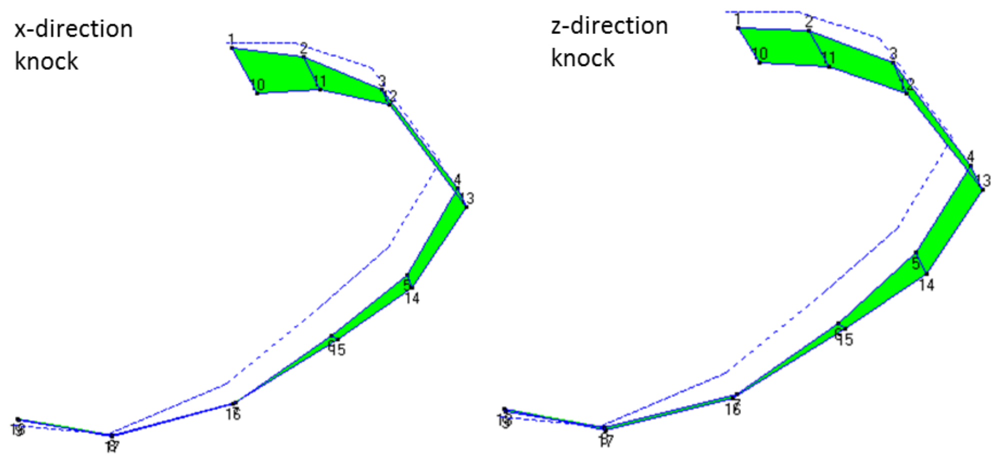

Figure S9: First bending mode of 9LO at 5.29Hz and 5.33Hz with free-free boundary condition knocked in X and Z-direction respectively