Journal of Physics: Conference Series

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To cite this article: D V Lim *et al* 2021 *J. Phys.: Conf. Ser.* **2120** 012014

15th International Engineering and Computing Research Conference (EURECA 2021) IOP Publishing
Journal of Physics: Conference Series **2120** (2021) 012014 doi:10.1088/1742-6596/2120/1/012014

Analysis of a Cam-Follower Mechanism for a Passive Parallel Lower Limb Exoskeleton

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Abstract. This project focused on the implementation of a novel cam-follower mechanism that was deemed to have good potential for practical application into a passive lower limb exoskeleton to determine its effectiveness in reducing the energy requirement of the user and its ability to match the walking gait of the user. The design of this novel-cam follower mechanism is inspired by the retractable mechanism of a ballpen. The cam follower mechanism was incorporated into a passive lower limb exoskeleton that was available prior to the study. Passive exoskeletons are intended to augment the load carrying capacity of the user through mechanical means instead of relying on external power. The walking gait study was conducted using physical testing. The mechanism was found to cause the user to bend below his natural centre of gravity a couple of times throughout the walking cycle. The user also had to stabilize himself from being rocked from side to side. Energy calculations were likewise conducted to investigate the energy consumption for a full cycle. The interchange among gravitational potential energy, spring potential energy and kinetic energy of the mechanism for a full walking cycle did not indicate possible advantage for the user.

1. Introduction

Exoskeletons has been developed since 1960 and have become a subject of interest in the fields of engineering and robotics which include prototyping and development, scientific research and publications and commercialized products [1]. Exoskeletons are used to augment the strength and durability of its user. There are different classifications of exoskeleton which include the type in which targeted body part is to be augmented, its system configuration and its dependency on its power source. There are three main classes of exoskeletons in terms of power dependency, which are the active systems, passive systems and hybrid systems [2].

Exoskeletons are implemented in a variety of applications such as industrial lifting, posture rehabilitation, lower limb rehabilitation [3] and military personnel augmentation. The concept of exoskeleton was originally a biological term which is used to describe the structure that provides the protection and support of soft organs for the bodies of animals [4]. The term exoskeleton in the engineering field is used to describe robotic devices that can be worn on a person to increase the functionality and ability of the person wearing it. In this research, the study is specific to focusing on the lower limbs of the human body, In lower limb exoskeletons, research is mostly done on the ability to reduce the energy exerted by the user to walk or perform daily task that involves footwork. Besides reducing energy exertion and consumption of the human body, lower limb exoskeletons have to be able to provide support as well as comfort to the user wearing it. Exoskeletons must be able to move naturally with the user and avoid causing any disruption to the walking gait of the user. The user should be able to walk or conduct activities normally without the hindrance of an additional support item being worn at the same time.

The movement of the lower limbs is governed by the hips, knees and ankles [5]. Each part has certain degrees of freedom and the exoskeleton must be able to facilitate and match the movements of the user as much as possible. The walking gait of a typical human does not vary much regardless of age or size. Walking involves a series of cyclic events known as the gait cycle. A gait cycle is completed when the strike of one foot finishes a successive strike of the foot from the same limb forming a pattern of events that allows us to walk forward. The walking gait cycle consists of two phases i.e., the stance phase and the swing phase. The stance phase covers approximately 62% of the cycle while the swing phase approximately 38% [6].

This project focuses on a novel cam-follower mechanism implemented into a passive lower limb exoskeleton intended to reduce the energy usage of the user while performing loading activities as well as match the user's natural walking gait. The cam-follower mechanism was ideated by K. M. Chan, a postgraduate at Taylor's University School of Computer Science & Engineering (SCE) [7] and was further followed up by C. S. Z. Soo, an undergraduate at SCE. While the basic design of the cam-follower mechanism was not changed, slight modifications were made to the orientation and dimension of certain parameters by Soo [8]. This cam follower mechanism design is based on the retractable mechanism found in retractable ballpens. The objective of this project is to determine the effectiveness of the cam-follower mechanism in matching the natural walking gait of the exoskeleton's wearer and its effectiveness in reducing the energy usage of the wearer.

2. **Methodology**

This research is the continuation of previous studies regarding the development and evaluation of the cam-follower mechanism. The methodology is elaborated in the following subsections.

2.1. Approach

Literature review was conducted on the cam-follower mechanism. The research findings and results from the previous project holders were also considered and both literatures were reviewed alongside journals articles on other passive parallel lower limb exoskeletons. Their shortcomings were identified and taken into account in determining the efficiency of the walking gait of the users when using the exoskeleton.

2.2. Prototyping and simulation

The design of the cam-follower mechanism was made and visualized with the help of SolidWorks. The exploded view function was helpful in the visualization. SolidWorks was likewise used for motion simulation during function which can be seen in its assembled form by changing the transparency of the exterior of the exoskeleton to provide a better visual of the interaction of the components located in the interior of the cam-follower mechanism once the 3D model has been assembled. Furthermore, SolidWorks was used to check that the components within the cam-follower mechanism do not collide with any other section of the prototype while also checking the respective components interaction to facilitate motion. This was necessary to identify errors that needed to be corrected before fabrication.

Once the design was verified, the components were simulated on ANSYS software to determine the stresses on the exoskeleton based on real life application whether it can support the user and a payload. The materials of the exoskeleton was chosen to ensure that the exoskeleton is light enough as to not burden the user but also strong enough to withstand its loads.

2.3. Manufacturing and testing

2.3.1. Manufacturing. The components for the exoskeleton were fabricated using CNC machining and 3D printing. Only one leg unit was fabricated to minimize cost by conducting preliminary testing beforehand. This was considered adequate as both sides are similar. Once the components have been fabricated, the prototype was assembled and checked for errors.

2.3.2. Testing. The assembled lower limb exoskeleton was tested using physical testing. The testing was conducted by firmly placing it to the side of the leg and attached with a few points of attachment to simulate the actual movement as it were a whole leg unit. Any unnatural movement is noted and noted down to keep track of any irregularities or changes being made into the user's natural gait due to its use. In ideal situations, the initial plan of measuring the energy usage of the user is by measuring oxygen saturation levels of the user while using the exoskeleton and observe the difference in oxygen levels of the user without the exoskeleton as a controlling variable [9]. This could have been done with the use of an oximeter in which the device is usually clamped to the subject's finger and the oximeter relays information concerning the rate of pulse oximetry of oxygen saturation levels in the user's blood; detecting the rate of depletion of oxygen levels while conducting activities with and without the exoskeleton [10]. However, the device was inaccessible due to the pandemic lockdown of university facilities. Only off campus physical testing of the prototype was possible at this point.

2.3.3. Energy Analysis. A theoretical energy analysis was conducted to identify the energy conversion at each point of the cam mechanism cycle. This involved analysing the interchange among gravitational potential energy, spring potential energy and kinetic energy of the mechanism for a full walking cycle to determine if there is any energy advantage for the user.

3. Results and Discussion

3.1. Prototype

The prototype used in this research as shown in Figure 1 was the modified design made by Soo [8]. The research objectives were to determine the effectiveness of the cam-follower mechanism in matching the natural walking gait of the exoskeleton's user and to determine the effectiveness of the mechanism in reducing the energy usage of the user while using the exoskeleton.

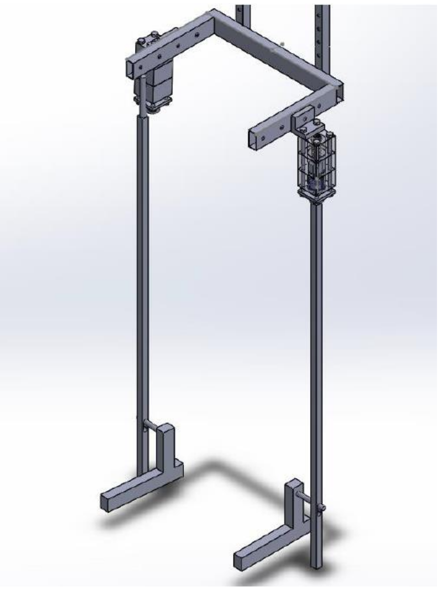

Figure 1. Modified design of the exoskeleton system by Soo

The design of the leg unit of the exoskeleton that houses the cam-follower mechanism consist of several components, each with a specific function. Firstly, the annular cam is a cylindrical component with a total of 6 V-shaped notches on one end as shown in Figure 2. The notches allow the ridged bushing to rest during the sequence transitions while it guides the rotational motion of the ridged bushing. At a certain height the ridged bushing is resting on the annular cam being pushed by the annular cam to lock it in the saw tooth profile. Next, the ridged bushing is a component with two angled extrusions at opposite ends of its circumference as shown in Figure 3. The extrusions are guide fins to lock the ridged bushing into the saw tooth cam-profile. The ridged bushing is the component located in the middle, in between the annular cam and the spring in the system. The ridged bushing undergoes rotational and translational motion from being pushed by the annular cam during each sequence.

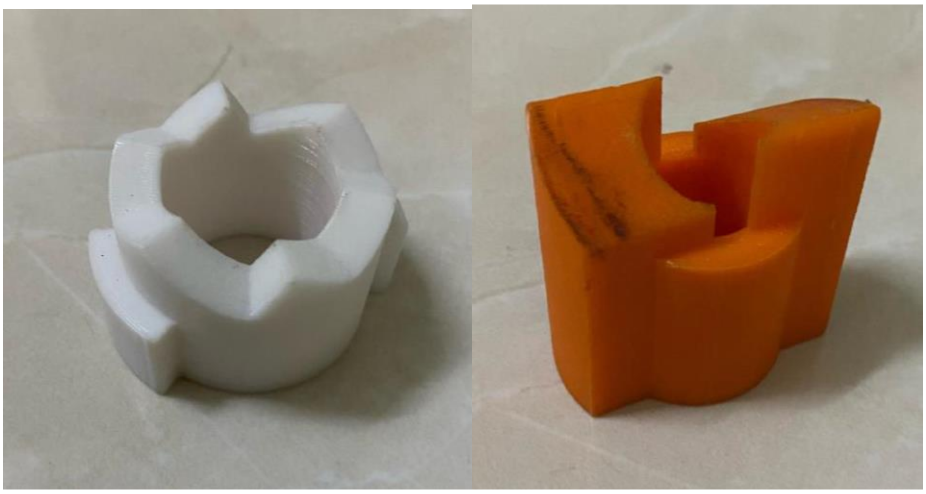

Figure 2 & 3 Annular cam of the leg unit (left) and ridged bushing of the leg unit (right)

Thirdly, the housing of the mechanism comprised of 3 different blocks which imitates the saw tooth cam-profile mechanism in a pen as shown in Figure 4. The three blocks comprise of the cam sleeve, spacer block and the top block., with the cam-sleeve being the bottommost block. The blocks assembled form the housing and also holds the spring inside the mechanism. The cam sleeve houses the annular cam and provides the saw tooth cam profile for the ridged bushing to lock itself into while the spacer block houses the ridged bushing and a portion of the spring. The top block houses the spring and completes the assembly of the mechanism housing. Lastly, the rod acts as the limb length connection between the cam-profile mechanism and the feet attachment point as shown in Figure 1. The rod is the stilt that allows the compression and extension of the spring in the mechanism to allow the mechanism to progress from one position to the respective sequence of events. The cylindrical section of the rod is the piece that works with the annular cam and the ridged bushing, which allows the components to easily rotate about the axis the rod. Along with the rod, an aluminum ring and the plate is attached to the rod; the plate functions to ensure that the leg unit of the mechanism is locked in place when the housing blocks are tightened as shown in Figure 5. The ring ensures that the annular cam functions to ensure the annular cam is pushed fully up and accordingly to the axis during the operation as shown in Figure 5 alongside the plate.

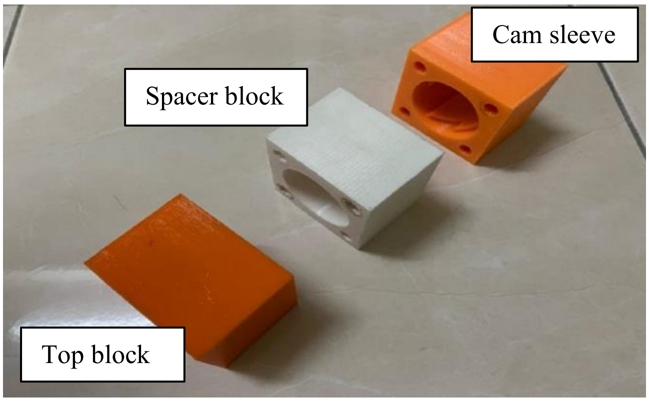

Figure 4. Disassembled housing block of the fabricated leg unit

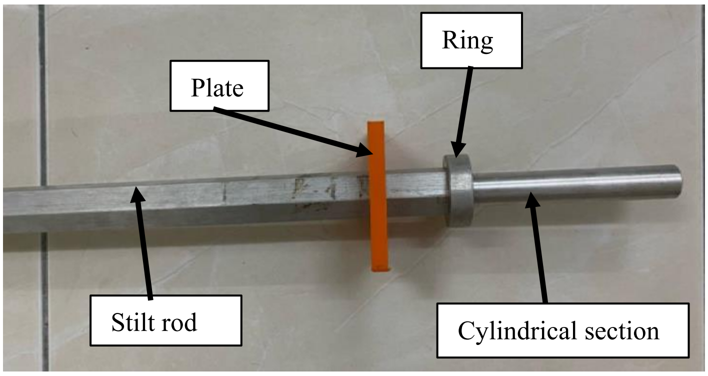

Figure 5. Stilt rod for leg unit and attached modifications and minor components

The assembled leg unit to be analyzed and tested is shown in Figures 6, 7 and 8. From the original design by Chan, the modifications done to the system included inverting the orientation of the ridged, in which Chan's design of the mechanism had the annular cam above the ridged bushing while Soo's design inverts the orientation of the respective two components, which now places the ridged bushing above the annular cam as shown in Figures 9 and 10. The modification was done to allow flexibility for the wearer to rotate their legs at the hip. The new arrangement causes less interference due to leg unit directly pushing the annular cam which in turn pushes and rotates the ridged bushing to avoid intermittent jamming due to the same leg rod that pushes the ridged bushing is also facilitating the rotational movement of the ridged bushing, Before the modification, there was more friction in the system and interference was experience during each cycle. The friction also prevents the ridged bushing from fully making contact with the annular cam on occasion and has caused wear in a few sections around the cam profile. The modifications made by Soo does not change the fundamental design base that was conceived by Chan, that being the cam-follower mechanism based of the cam-follower mechanism of a retractable pen.

Figure 6. Image of the prototype leg unit for one leg

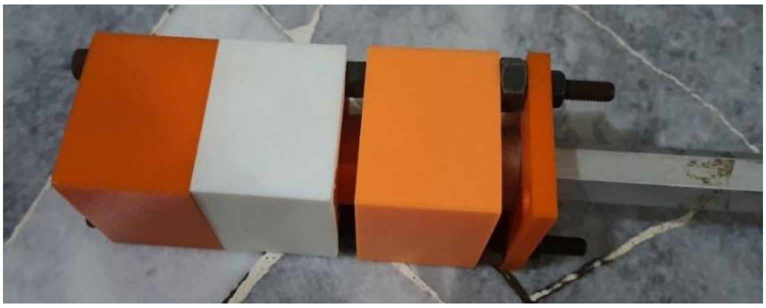

Figure 7. Updated closeup of the prototype leg unit with its segmented sections

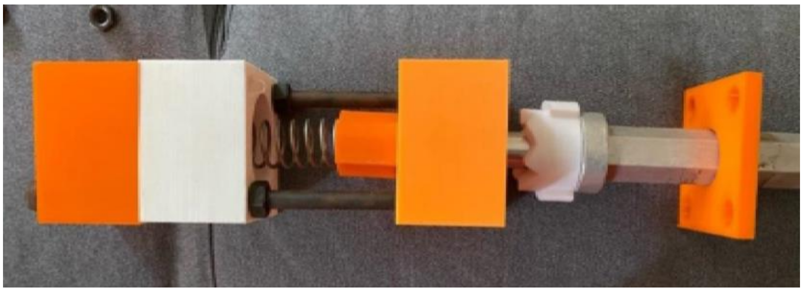

Figure 8. Unassembled exploded view of the prototype leg unit assembly

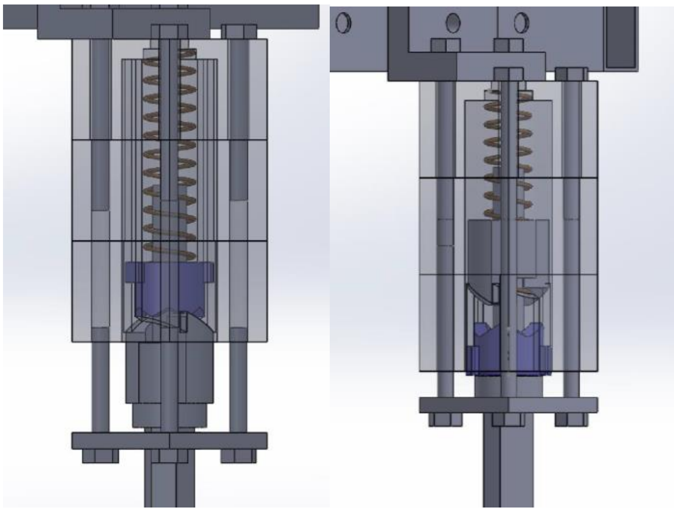

Figure 9 & 10. The original design by Chan (left) with the annular cam above the ridged bushing and Soo's modified inverted design (right)

3.2. Motion Analysis

Body posture is referred as the position of one's body in a spatial setting in which the body joints is responsible for the alignment of the body parts in relation to each other corresponding to the environment at a certain point in time [11]. Posture of the body is important to ensure one's balance is maintained against gravity and achieve stabilization of the body during voluntary movements. In an ideal situation, the posture of the person standing upright would be with both feet and body are in a parallel plane while stationary. Considering this ideal situation, the user should be standing with a straight, upright posture as shown in Figure 11. The green blocks represent the cam-follower mechanism housing which are supposedly located at the side of the hips when the exoskeleton is worn and the red rods represent the stilts rods that make up the leg unit of the exoskeleton.

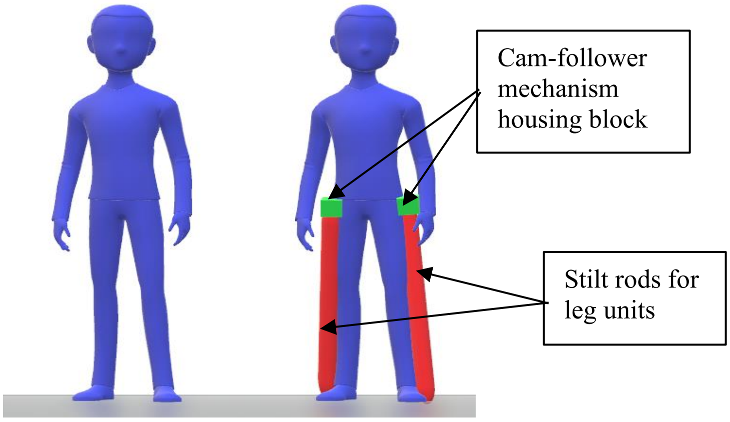

Figure 11. Ideal posture of a person standing without and with the exoskeleton

The mechanism will be reviewed through one limb first (Limb A) before being compared to the sequence of the opposite limb (Limb B) as shown in Figure 12. The following explanations will be based on Figure 13 which show the movement sequence of the cam mechanism. The numbers marking each position of the mechanism are identified as 1, 2, 3 and 4. It is noted for visualization purposes, that position 1 occurs when the spring is fully extended which pushes the ridged bushing towards the annular cam and while in position 3 the spring is kept compressed by the ridged bushing being locked in the cam-profile of the housing block.

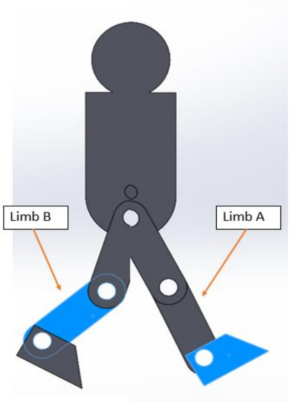

Figure 12. Diagram indicating the two lower limbs of a human which was separately analyzed

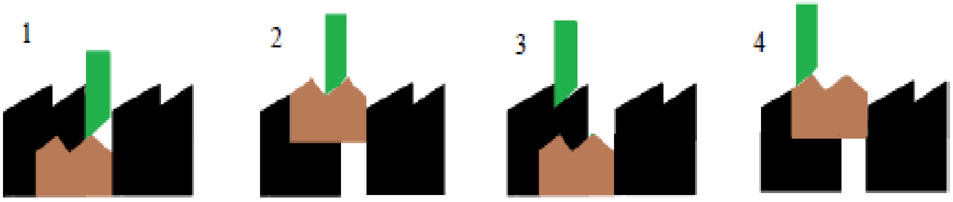

Figure 13. Movement of cam-follower mechanism shown in order of sequence (positions 1, 2, 3 and 4) with 1 being the default position of standing before the heel strike [7]

The spring constant. k was calculated first to be substituted into the equation to calculate the spring energy using the equation:

$$Spring\ constant, k = \frac{Gd^4}{8nD^3} \quad \dots\ (1)$$

In which, G is the shear modulus of the spring; d is representing the spring coil diameter; n is the number of turns on the spring and D is the mean diameter of the spring. Substituting into the equation;

$$k = \frac{(77.2\ GPa)(2.032mm)^4}{8\ (11)(22.968m)^3} = \ 1234.41\frac{N}{m}$$

The identified spring rate of the spring is 1234.41 N/m, which will be used to calculate the spring energy at different transitions between sequences.

It is also noteworthy that the free length of the spring is 85 mm. During the full cycle of the cam-follower mechanism, the spring is first compressed at position 2 which happens immediately after the heel strike. The body weight and the gravity help the user to compress the spring to transition into position 2. From position 2 transitioning into position 3, the ridged bushing will slide into the cam profile of the block and lock itself, which causes the spring to still partially compressed to push and hold the ridged bushing in place. During this sequence, the spring could only extend at a certain length before the user would have to expend their own energy to lift the rest of the un-extended length. During the transition from position 3 to position 4, the spring must be compressed again to dislodge the ridged bushing from the cam profile and provide the clearance height for the ridged bushing to move into the spring's compressed state in position 4. During this, the user's weight and gravity aids the compression of the spring. From position 4 to 1, the spring will work against gravity (body weight) to push the ridge bushing into position 1, in which the rod of the leg unit will be fully extended again. This will bring the mechanism back to position 1 to restart the cycle.

Based on Figure 14, Position X is the default position of standing which is also the position in which the cam-follower mechanism is at sequence 1, in which the spring is fully extended. From X, the leg swings from X to A to B. At B the feet will start to make contact with the ground. From B to C, the cam-follower mechanism transitions from position 1 to 2 as upon the heel strike, the user has to bend their body much lower to compress the spring to push the ridged bushing in mechanism to get it to rotate and lock the ridged bushing into the cam-profile of the cam-follower housing. At the transition of position1 to position 2, the spring has to be compressed at a certain height to provide sufficient clearance for ridged bushing to slide into its locked position before position 2 transitions into position 3.

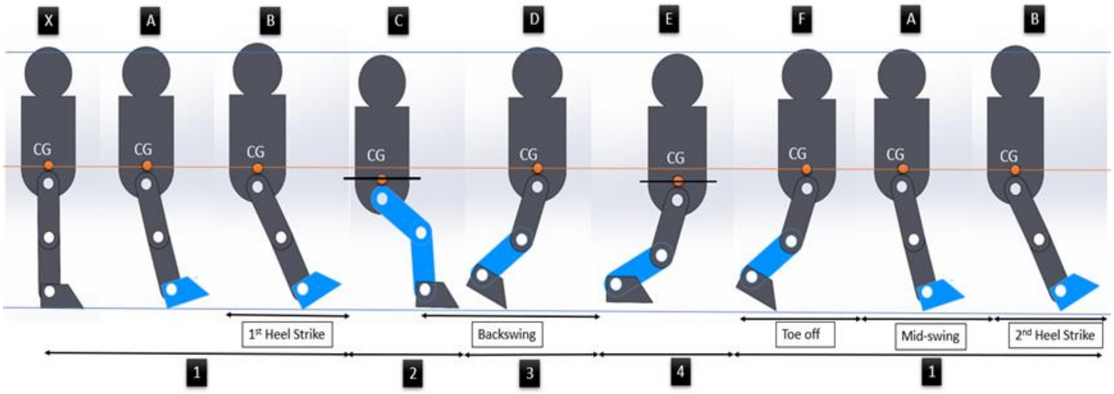

Figure 14. Walking gait observation of Limb A through physical prototype testing with numbering sequence reference to Figure 13, with shown center of gravity (CG)

Finding the minimum height clearance for the ridged bushing:

$$Minimum\ height\ clearance\ for\ ridge\ bushing = Cam\ profile\ height - Annular\ cam\ height$$
$$= 45.392\ mm - 27\ mm = 18.392\ mm$$

Substituting into the energy equation to obtain the spring energy, K;

$$Kinetic\ energy, E = \frac{1}{2}mv^2\ \ldots\ (2);$$

$$Energy\ needed\ to\ compress\ the\ spring\ (position\ 1-2) = \frac{1}{2}(1234.41)(0.019)^2 = 0.22281\,J$$

Hence the amount of energy required to compress the spring enough from sequence 1 to 2 to provide clearance for the ridged bushing to slide into its locked position is 0.22281 J.

Next, from position 2 to 3, the ridge bushing will be pushed by the spring to its locked position with the spring compressed and the ridged bushing locked in place in the cam-profile. This occurs at position C to D shown in Figure 14. During this transition, the user would have to get back to his normal height without the full energy of the spring as a part of its length is now compressed and held in place by the locked ridged bushing. The length of the spring at position 3 is found to be approximately 70 mm. When subtracted by its free length, the compressed length is 15 mm. From the compression of 19 mm in length at position 1 to 2, the spring is only able to push the spring out 4 mm, which is obtained when the length of the spring at position 3 is subtracted from the length of compression. This results in only 4 mm of extension of the spring.

$$Energy\ provided\ by\ the\ spring\ to\ push\ back\ from\ compressed\ state\ (position\ 2-3)$$
$$= \frac{1}{2}(1234.41)(0.004)^2 = 0.00988\,J$$

Hence the amount of energy the spring could provide to lift the person back up from their lowered position and give energy for the backswing from C to D is approximately 0.00988 J for the user to regain their default height and to push the body during the backswing. The amount is very low and does not benefit the user due to its short extension when the ridge bushing is locked.

From position 3 to 4, the spring must be compressed again to release ridged bushing from its lock position and attain sufficient height for it to slide into the free state at position 1. For position 3 to transition to position 4, the user has to bend again at a somewhat uncomfortable position for the spring to be fully compressed to free up space for the ridged bushing to slide out of its locked position. The spring will have to be compressed approximately 10 mm more to push the ridged bushing guiding fin out of the cam-profile. It is noted that at position 4, the spring would be at a length of 60 mm after it is compressed 10 mm more from the original length of 70 mm at position 3.

$$Energy\ needed\ to\ compress\ spring\ (position\ 3-4) = \frac{1}{2}(1234.41)(0.01)^2 = 0.06172\,J$$

Hence, the amount of energy needed to compress the spring to dislodge the ridge bushing to be pushed out in the next sequence is approximately 0.06172 J.

At the final transition from position 4 to position 1 is when the toe off happens and it takes places as soon as position 4 is reached. The spring will now fully extend back to its original free length, and this extension aids with the propulsion phase in the walking gait cycle. In sequence 4, the spring was compressed to 60 mm length, therefore it will extend 25 mm in transition to position 1. The calculation for the propulsion at the toe-off is as follows.

$$Energy\ provided\ by\ the\ spring\ for\ propulsion\ at\ toe-off\ (position\ 3-4) = \frac{1}{2}(1234.41)(0.025)^2 = 0.38575\,J$$

A total of 0.38575 J is provided to the user of the exoskeleton during the toe-off to propel their body forward from position 4 back to position 1 for the start of the next walking cycle.

Figure 14 also shows the person's center of gravity which is usually located near the sacrum of the person [12]. It is observed that at positions C and F, the body's center of gravity is below the line of neutral center of gravity. This happens during each compression sequence, which are represented by positions 2 and 4 in Figure 13. This causes the user to have to constantly lower their body to compress the spring in the cam-follower mechanism.

When a person walks, each leg alternates its movements to the other limb. Therefore, if Limb B were to have the same flow of sequence as limb A; for example, having the heel strike at sequence 1 and so on forth, Limb B would have to be at a different sequence at the start of the walking gait cycle due to the fact that both limbs cannot be in the same phase at the same time. Hence since Limb A would start at the heel strike at position 1, Limb B would have to start at position 3. Hence the flow would be position 3, 4, 1 then 2 as opposed to the flow sequence for Limb A, which is in the flow of position 1, 2, 3 and 4. Hence the positions of the leg would also be changed as well. This indicates that during standing (Position X), each leg is on two different sequences; Limb A would be in position 1 and Limb B would be in position 3 or vice versa.

Due to this the user will tend to be in an off-center state while standing as shown in Figure 15. In position 1, the leg unit is fully extended since the spring fully extended itself, whereas at the opposite leg, the cam-follower mechanism is in position 3 and the spring is compressed which decreases the extended length of the leg unit. This posture will also persist during walking and therefore causes the user to rock from side to side while walking, as shown in figure 15. Therefore, the walking gait of the exoskeleton did not fully match the user's natural walking gait.

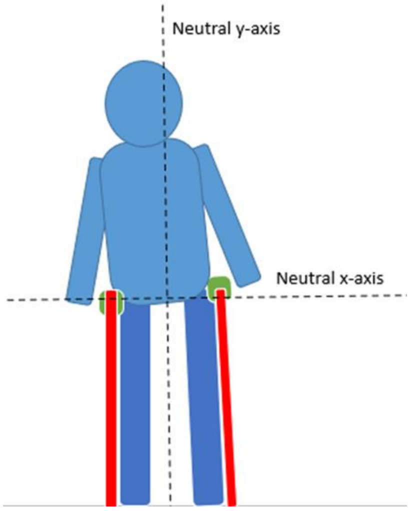

Figure 15. Diagram representation of unbalanced posture when standing with the exoskeleton

4. **Conclusion**

Based on the study carried out, the cam-follower mechanism incorporated into a passive lower limb exoskeleton was unable to match the walking gait of the user. The results obtained through physical testing showed that the exoskeleton wearer had to make adjustments to his height at certain parts of the waking cycle. This issue is exacerbated with the constant tilting of the body due to alternating lengths on opposite limbs shown in Figure 15.

Each compression and extension of the spring occurred at different positions of the walking gait, and while there were instances that conformed to the ideal transfer of energy, it was observed that in the transition from position 2 to 3 the energy provided to push body upright and the leg back for the backswing could not synchronize with the walking cycle, hence the user could not benefit from the spring's extension. The only instance thar the spring provided energy to complement the user is during position 4 to 1 were the extension of the spring coincided with the leg extension.

While the cam-follower mechanism would not be considered suitable for use in a passive parallel lower limb exoskeleton, the knowledge gained and findings obtained from this study can help to add to the body of knowledge for the design of passive parallel lower limb exoskeletons.

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