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Walking Simulator Mechanism

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Cover Page Footnote
We would like to thank our professor, Dr. Jason Halloran, for his guidance and support throughout this project. Dr. Halloran is an assistant professor in the mechanical engineering department at Cleveland State University and co-director of the Mechanics and Control of Living Systems Laboratory (www.mclslab.com). We would also like to thank Sarah Popernack for being the test subject used to gather the human motion data for this project.

Abstract

This paper presents the design, simulation, and kinematic evaluation of a mechanism aimed at simulating both the motion and ground reaction forces produced by a human foot while walking. Such a mechanism can be used to test the durability of shoes through life cycle analysis. In attempting to mimic the physical motion of the human foot as closely as possible, the forces experienced by the human foot were also accurately replicated through the incorporation of a non-stationary testing platform. As is shown in the paper, this testing environment allows for simple adjustments to be made in order to simulate different body weights as well as different walking surfaces.

1. Introduction

In engineering, testing the durability of a product using methods such as life cycle analysis is a crucial element in the design process, and often dictates if a product is suitable for use. To accurately test the durability of any product, conditions encountered during actual use must be accurately simulated. In this paper, the design of a walking simulator mechanism is presented that could be used for testing shoes. Focus was put on the motion of the human foot and ground reaction forces that occur while walking. These forces acting on the shoe, as well as their directions, can substantially affect its durability. A qualitative synthesis was first performed to evaluate possible solutions and the path required for the mechanism to take, followed by an analytical synthesis.

2. Design Process

In order to estimate the path of a human foot while walking, videos were recorded of a human walking, filmed from a side view along with other various views. The footage was processed using a kinematics software package, Kinovea, which traced the paths that the knee, ankle, toe, and heel took (Figure 1). This aided in further understanding and analyzing the forces that are produced by these paths. Since a specific sequence of forces is generally tied to a specific motion pattern, great focus was placed on path generation while designing the mechanism. If designed successfully, a final mechanism which mimics the motion of the human foot should also produce the same forces that a shoe would endure during real use. It was determined that a three position synthesis was needed in order to design the mechanism. The three positions that were defined were stance, toe off, and heel strike. It is desired to reach these three positions in a certain order beginning from heel strike and moving to stance and toe off.

The design of the walking simulator began with the knee. Initially, the Hrones and Nelson Atlas (a handbook of sorts containing predesigned kinematic mechanisms) was searched in order to find a mechanism that would output a similar path to that observed in Kinovea, however, a close match could not be found. As shown in Figure 1, the knee produces a complex path that is difficult to replicate. Therefore, it was appropriate to simplify the path using a Grashof linkage similar to Chebyshev's approximate circle-tracing four bar mechanism (Figure 2). This linkage is controlled with a motor driving the crank (link 2). A mechanism close in resemblance was replicated and scaled in SolidWorks, retaining the motion required for the operation of the knee. The length of the crank link was increased, creating a “teardrop” shape (Figure 3) that more accurately traces out the path of the actual human knee. This teardrop path also produced motion at the foot which more closely mimicked that of the human foot, as was demonstrated during analysis of the entire mechanism, shown later in this paper. This allowed for the foot to smoothly come off of the ground between heel strike and toe off instead of merely dragging along the ground.

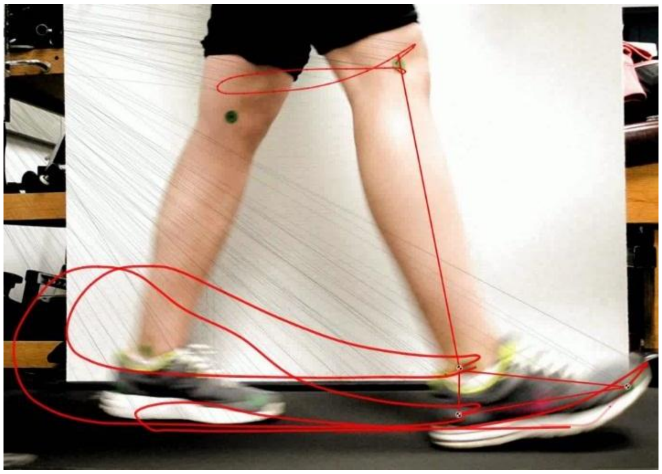

Figure 1: *Paths of knee, toe, ankle, and heel traced in red for one cycle of the front foot of the test subject. Paths generated automatically using Kinovea software package based on placement of markers on the foot and knee.*

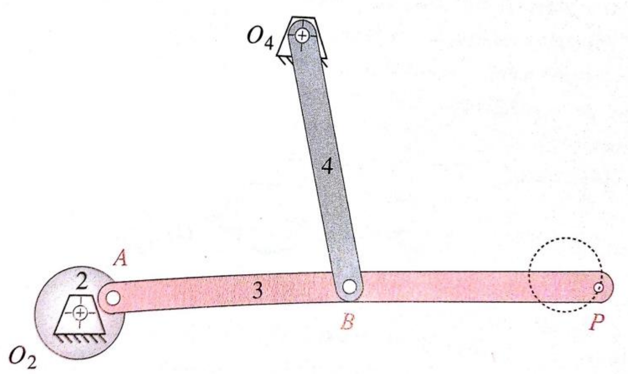

Figure 2: *Chebyshev's approximate circle-tracing four bar mechanism used as the starting point for the design of the knee mechanism. Point P traces an approximately circular path and link 2 is the driving link (crank). Photo credit: "Design of Machinery" by Robert L. Norton*

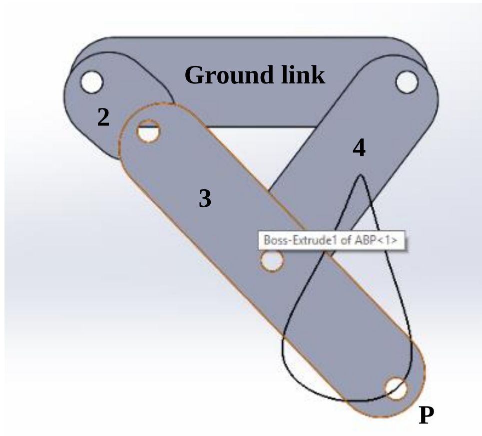

Figure 3: *Redesigned version of Chebyshev's linkage, with crank (link 2) lengthened to create teardrop path at point P.*

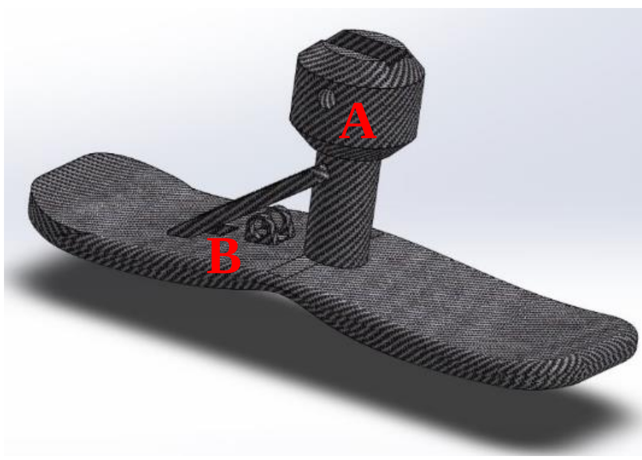

Figure 4: *Foot link, designed in SolidWorks. One leg link is attached to point A and the other to point B.*

A binary link was then attached to point P of the coupler of the knee. This link represents the lower leg of a person and its length corresponds to the lower leg length of the test subject. The end of that link was attached to a foot link (Figure 4) which replicates a human foot and can be housed in a test shoe for testing. The foot profile was created by making simple spline curves in SolidWorks which were roughly based off of the aesthetics of professor Hugh Herr's (MIT Media Lab) prosthetic foot. A second binary link connects the back of the foot link to the crank of the knee. This dual link design is analogous to the anatomical design of the human leg and foot. With this combination of mechanisms, the foot link is able to closely replicate a path similar to a human's foot walking in place (Figure 5).

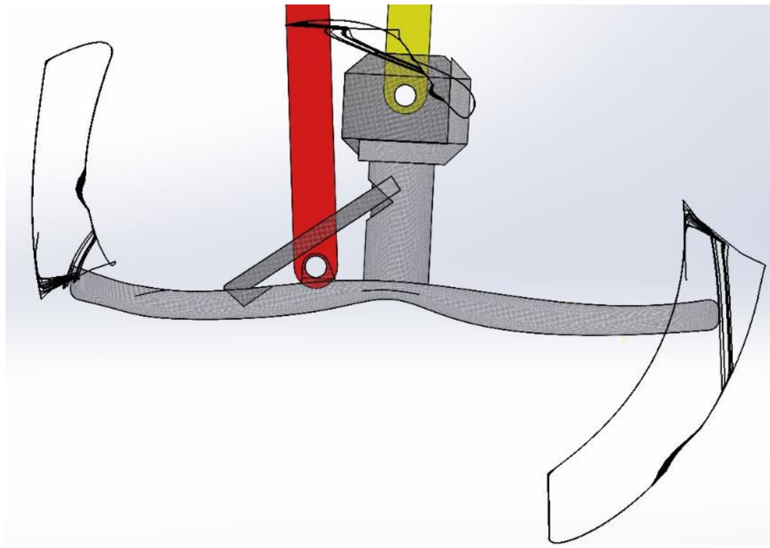

Figure 5: *Side view of the foot link with the two binary leg links attached. The motion paths created by the toe, heel, and ankle through multiple walking cycles are traced in black.*

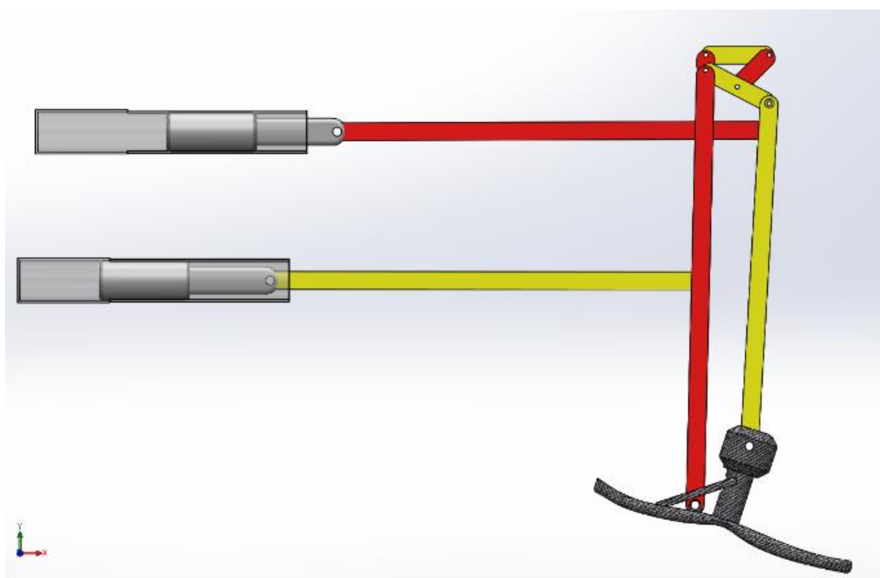

Figure 6: *Final mechanism design, with crank-sliders added to both links for constraining the motion of the foot.*

The current mechanism was comprised of two four-bar linkages. The bottom four-bar linkage (including the two leg links, the foot link, and link 3 of the knee) had an infinite number of circuits through which it could move, causing random motions to occur during each cycle. To fully define the operating parameters of the mechanism, one non-actuated crank-slider (piston) mechanism was added to both the front and back leg links (Figure 6). The locations chosen to attach the crank-slider on the links were somewhat arbitrary, though effort was made to locate portions of the links which had the most movement, in order to more precisely restrain the motion of the mechanism. The housing of the piston was optimally designed to restrain the motion of the link between the minimum and maximum positions of the desired circuit. The new mechanism produced a desired and defined path of motion. Furthermore, the linkages are now fully defined throughout the entire range of motion and hence the mechanism remains in the same circuit consistently.

With the foot behaving as desired and in a consistent fashion, a method for moving the foot forwards and backwards had to be designed in order to fully simulate walking. In the human leg, this is done by the movement of one's knee caused by the contraction of the upper leg muscles. For simplicity concerns, the addition of more motors or links to the mechanism had to be avoided. Therefore, instead of making the foot move, it was decided that perhaps the testing ground could move instead.

A treadmill was used under the foot to simulate the horizontal walking component as well as to compensate for the vertical movement of the foot (Figure 7). The treadmill is attached to the ground via springs, so that the height of the treadmill changes according to the position of the foot during its walking cycle. For instance, at toe off, the foot pushes downwards. This would usually cause the human's body to move up, but in this case it will push the treadmill down. In this configuration, the relative motion between the foot and the treadmill will mimic the motion of a person walking.

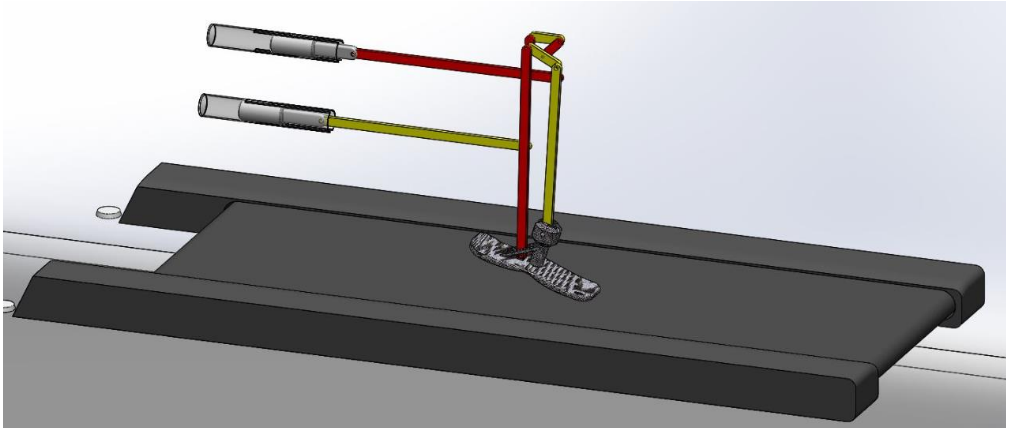

Figure 7: *Walking mechanism placed on a treadmill to mimic the horizontal and vertical motion seen by the human foot during walking. Spring system used under the treadmill to facilitate the vertical motion is not shown.*

The belt of the treadmill is only moved by the force that the foot exerts on the treadmill itself, which adds to the realism of what a shoe would experience in terms of friction and force while in use. Different walking conditions and coefficients of friction may be simulated by lining the treadmill belt with different materials. Furthermore, a force analysis between the foot and the treadmill surface can be conducted. Changing the spring constant during that analysis will simulate weights of different individuals. This is a key feature because it allows the mechanism to be easily adjusted for different people wearing a shoe.

3. Analysis and Results

The goal of this mechanism is for the foot to achieve ground reaction forces and a motion similar to that of a human foot while walking. However, it is still important to analyze the knee mechanism in order to better understand the kinematics of the mechanism as a whole. A position, velocity, and acceleration analysis of the endpoint of the coupler, point P was therefore conducted (Figure 8). The analysis yielded smooth, continuous functions for both the velocities and accelerations of the knee, ensuring safe and proper operation of the entire walking simulator.

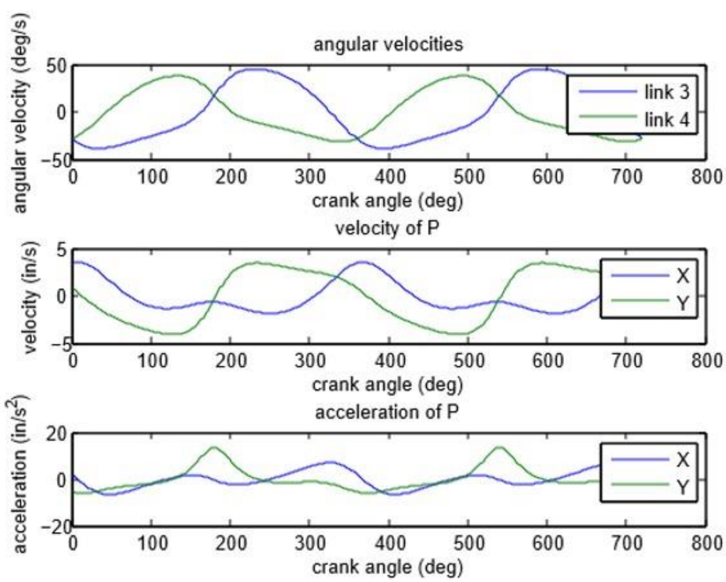

Figure 8: *Graphs of the motion experienced by the knee mechanism through multiple operation cycles. All graphs have the crank (link 2) angle in degrees on the horizontal axis. The top graph shows the angular velocities (degrees/s) of link 3 (blue) and link 4 (green). The middle graph shows the velocity (in/s) of point P (x-direction velocity in blue, y-direction in green). The bottom graph shows the acceleration (in/s^2) of point P (x-direction velocity in blue, y-direction in green).*

In SolidWorks, the paths of the toe, heel, and ankle were traced during several cycles and were found to be very similar to those created by a walking human ("walking-in-place" rather than moving forward). The paths have a bean-like shape, which is similar to the paths traced on the test subject (Figures 1, 5). The paths are slightly different from iteration to iteration due to the way the pistons restrain the motion of the connecting links. This can be corrected in one of two ways: a) more precisely define the minimum and maximum positions that the pistons can move through; or b) increase the damping coefficient in the spring on the treadmill to ensure smoother motion of the device (this is the preferred solution as it gives more stability to the entire system).

The forces generated by the contact of the foot and the surface of the treadmill are plotted below (Figure 9) and are very similar to the forces generated by a real person walking (Figure 10). A human foot experiences a peak ground reaction force of 2.4 times the weight of the walking body. The peak force experienced by the foot mechanism is around 1690 N, which is 2.4 times the weight of the 70 kg test subject used. As mentioned before, the spring constants used under the treadmill can also be adjusted so that walking of different size humans can be properly simulated.

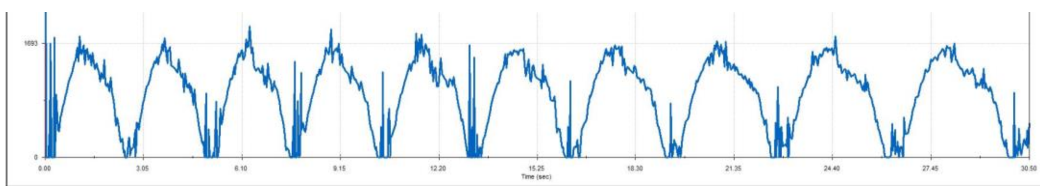

Figure 9: *Graph of ground reaction forces (N) experienced by the foot mechanism, plotted against time of motion of the foot (s).*

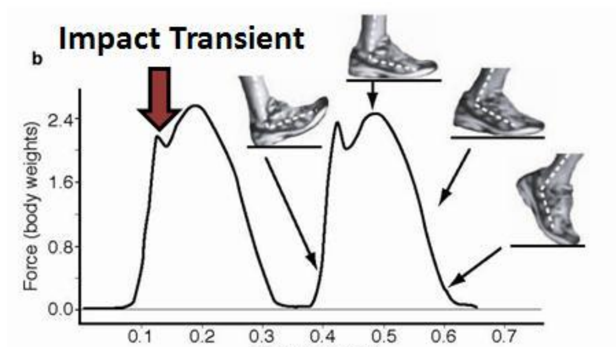

Figure 10: *Graph of ground reaction forces (in multiple of body weights) experienced by a human foot during walking, plotted against time of motion (s). Photo credit: Lieberman, Daniel E., et al.*

There is a slight phase shift noticed between the graphs. Ideally, the maximum ground reaction force experienced by the foot should occur when the foot is fully flat on the ground. However, the mechanism has a longer toe off period, causing the reaction forces to occur during the beginning of the toe off phase. The heel strike and end of the toe off phases experience appropriate forces when compared to an actual human walking, so the discrepancy is minor.

Two possible solutions exist to fix the dissimilarities in the phase shift for the ground reaction forces. One solution is to redesign the lower four-bar mechanism of the walking simulator to allow for a longer stance phase. The current stance position is too short, causing the phase shift of the walking cycle. This can be done by modifying the three position synthesis to elongate the stance phase. Another solution is to design a foot that undergoes flexion upon commencement of toe off and heel strike, which will yield a smoother transition of forces and a more accurate simulation of the walking dynamics. Furthermore, the bottom profile of the foot attachment should ideally be optimized to look more like a real foot or at least should be based off of some model that will allow for a more accurate distribution of forces.

An analysis of the motor was also conducted, revealing the power (Figure 11) and torque (Figure 12) required throughout the cycle. The current motor has a constant angular velocity of 15 RPM. The mechanism will require a 300 watt, 100 N-m motor to drive the crank of the knee mechanism for simulating the walking of a 70 kg human. Likewise, plots of the velocity (Figure 13) and acceleration (Figure 14) at the toe of the foot are also presented for a complete motion analysis of the mechanism.

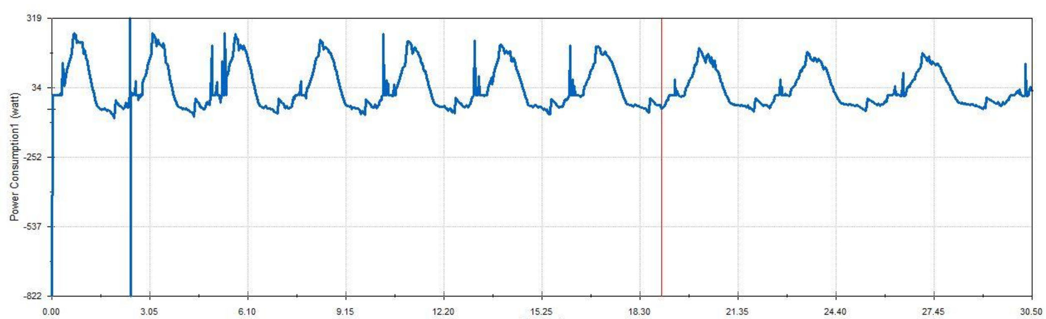

Figure 11: *Power of the motor driving the crank, in watts, plotted against time, in seconds.*

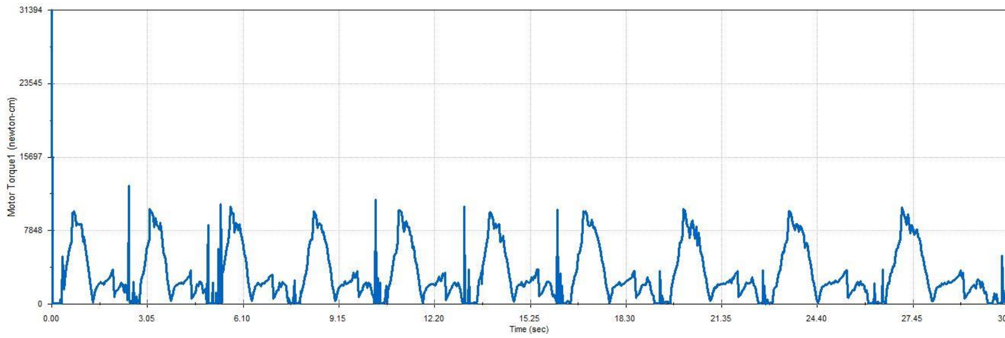

Figure 12: *Torque produced by the driving motor, in N-cm, plotted against time, in seconds.*

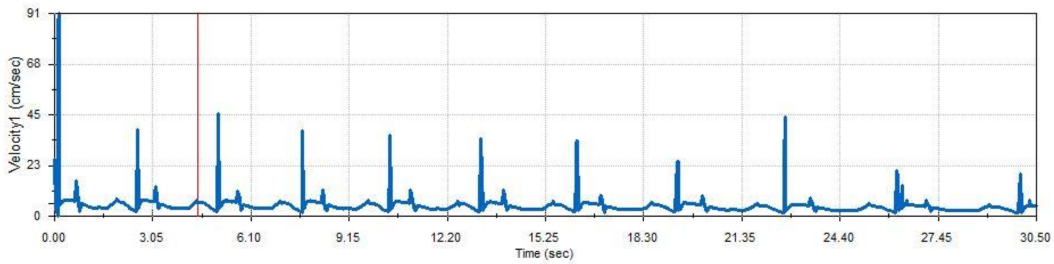

Figure 13: *Plot of velocity (cm/s) of the toe in time (s).*

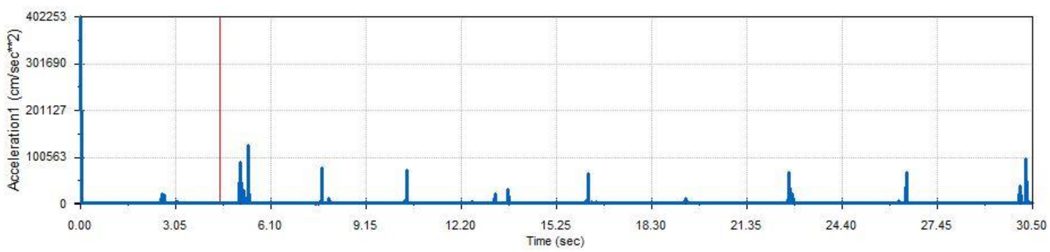

Figure 14: *Plot of acceleration (cm/s^2) of the toe in time (s).*

The transmission angle between the coupler and rocker (links 3 and 4) of the knee was also analyzed (Figure 15). For less than half of the cycle, the mentioned links experience transmission angles between 27° and 47°, which is not optimal and causes high torques to occur at the links and adjoining joint. This could be corrected through further design optimization such as adjusting link lengths of the knee mechanism.

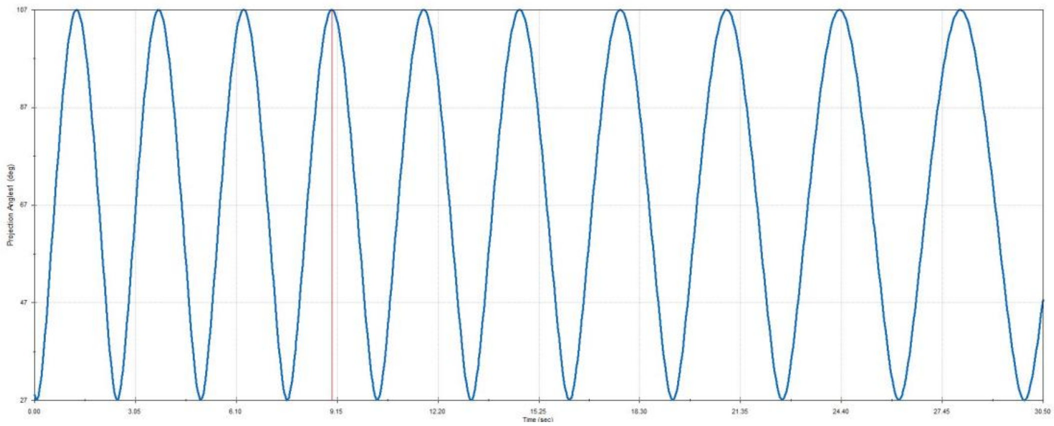

Figure 15: *Plot of transmission angle (between link 3 and link 4 of the knee), in degrees, during the time (s) of motion of the walking simulator.*

While the created mechanism meets the performance parameters required to mimic the motion and ground reaction forces of the human foot, it is very complex and perhaps not ideal for mass manufacturing. Simplifications should be made, especially in regards to the design, sizing, and positioning of the pistons used for constraining the motion of the foot. Future work may also consider an optimal way of fixing the mechanism, treadmill, and spring system on a stationary testing platform for continuous use.

4. Conclusion

The walking simulator mechanism presented in this paper closely mimics the walking path of a human foot. According to previously conducted tests, a human foot experiences a peak ground reaction force of 2.4 times the weight of the walking body. In the analysis of the walking simulator, the peak force was found to be 2.4 times the weight of the 70 kg test subject, which matches the theoretical value. It is also possible to adjust the forces on the foot for heavier individuals by simply increasing the spring constant of the spring between the treadmill and the ground to achieve the required forces on the foot. Future work should optimize the mechanism for simplicity of production and for increased accuracy, as described in the *Analysis and Results* section. Figure 16 shows four phases of the walking simulator mechanism while moving through a walking cycle. Phase 1 is heel strike, phases 2 and 3 are transition phases (stance phases) from heel strike to toe off, and phase 4 is the end of the toe off phase. Please visit www.tituslungu.com/walksim.html for a video of the walking simulator mechanism in action.

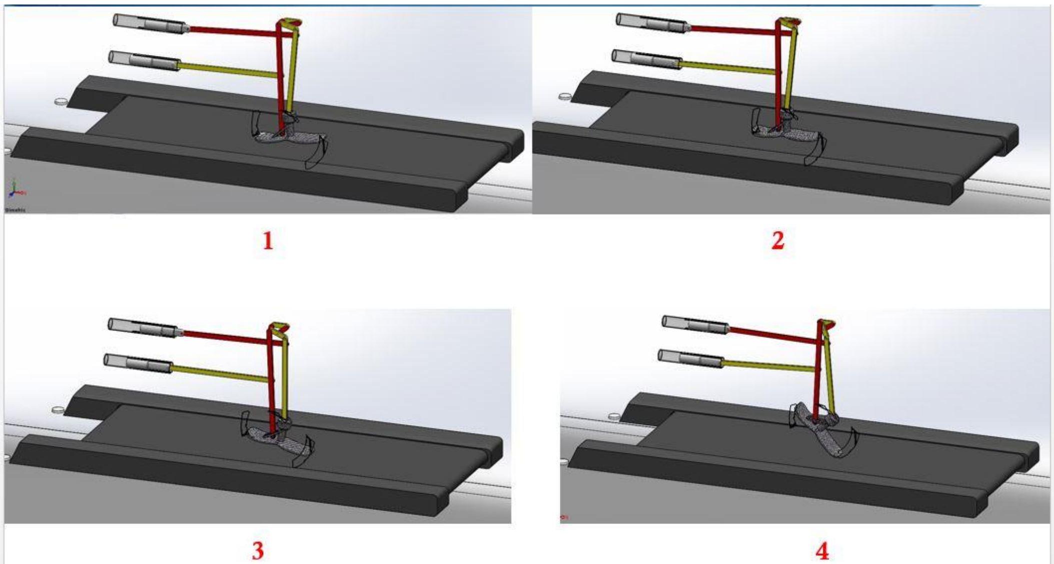

Figure 16: *Motion of the walking simulator depicted in four phases, comprising one cycle (one full step of the foot). Phase 1 is the heel strike phase. Phases 2 and 3 are transitional phases (stance phases). Phase 4 is the toe off phase.*

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